Observation of *CP* violation in charm decays at LHCb

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54th Rencontres de Moriond 2019

Electroweak Interactions and Unified Theories Session

21 March 2019

Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

CP violation history

1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
***CP* violation in K**
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

2001
Beauty particles:
***CP* violation in B^0**
meson decays
BaBar and Belle
collaborations

2019
Charm particles:
***CP* violation in D^0**
meson decays
LHCb collaboration

TODAY

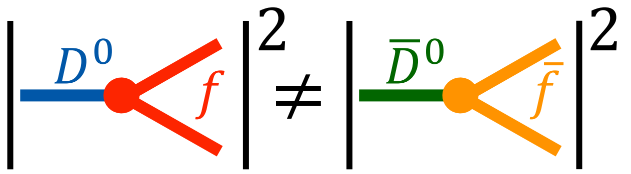
CP violation in charm

- *CP* violation in the charm sector **not observed** yet
- Charm decays allow *CP* violation to be probed with an **up-type** quark
- **Complementary** to studies with K and B mesons
- SM predictions difficult to calculate, but small *CP* asymmetry is expected ($\sim \mathbf{10^{-4} - 10^{-3}}$)

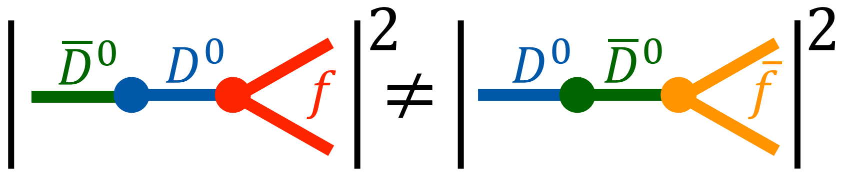
Direct and indirect CP violation

$$A_{CP}(f) = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \bar{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \bar{f})}$$

- **Direct** *CP* violation when $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$



- For **oscillating neutral** mesons $|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$
  - *CP* violation in **mixing** when $|p| \neq |q|$
  - *CP* violation in **interference** between decay and mixing when $\arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq -\arg\left(\frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}}\right)$



$$x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

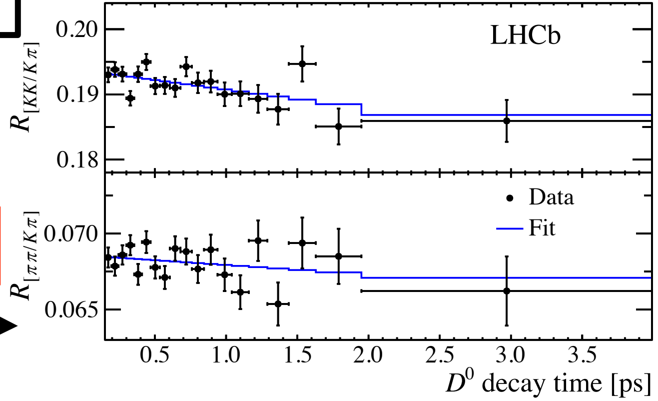
Parameter	Avg value (HFLAV 2018) [%]
x	$0.36^{+0.21}_{-0.16}$
y	$0.67^{+0.06}_{-0.13}$

Mixing and CP violation

Run 1
$(3\ \mathrm{fb}^{-1})$

- **Measurement of y_{CP} with $D^0 \to h^+h^-$**
  - $y_{CP} = [0.57 \pm 0.13\ (\mathrm{stat}) \pm 0.09\ (\mathrm{syst})]\%$
  - Compatible with and precise as the **World Average** $(0.84 \pm 0.16)\%$

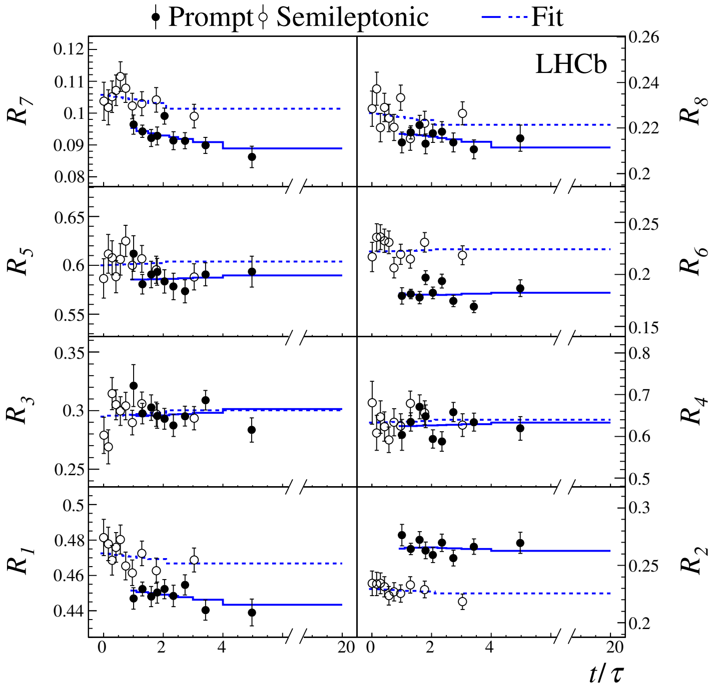
PRL 122 (2019) 011802



- **Measurement of x_{CP} and Δx with $D^0 \to K^0_S\pi^+\pi^-$**

arXiv:1903.03074

  - $x_{CP} = [0.27 \pm 0.16\ (\mathrm{stat}) \pm 0.04\ (\mathrm{syst})]\%$
  - $\Delta x = [-0.053 \pm 0.070\ (\mathrm{stat}) \pm 0.022\ (\mathrm{syst})]\%$
  - **Most precise** determination of x from a single experiment
  - Combination with current global knowledge gives **$x > 0$ at more than 3σ**



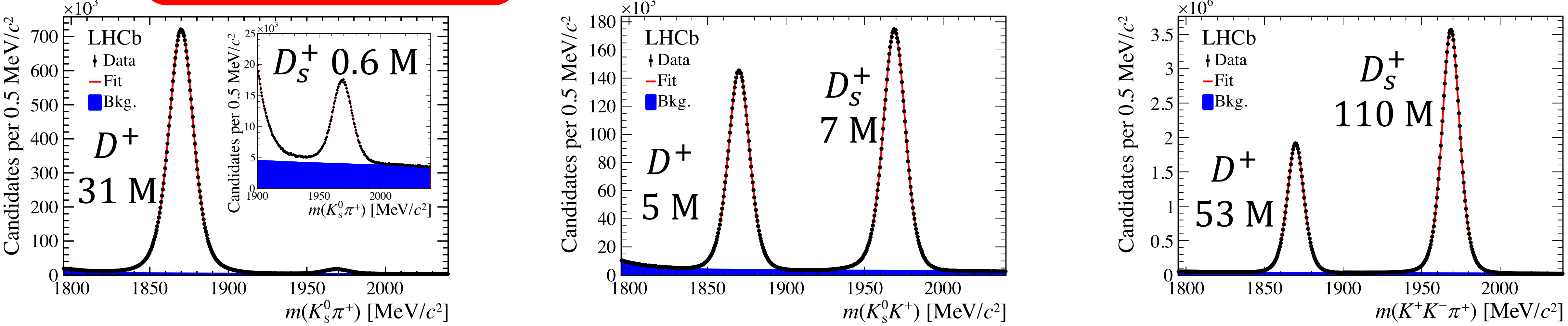
No CP violation observed

Search for direct CP violation

- A_{CP} in $D^0 \to K_S^0 K_S^0$ → see talk by Giulia Tuci at YSF
- A_{CP} in $\boldsymbol{D_s^+ \to K_S^0 \pi^+}$, $\boldsymbol{D^+ \to K_S^0 K^+}$, $\boldsymbol{D^+ \to \phi\pi^+}$: arXiv:1903.01150

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (\ \ 1.3 \ \pm 1.9 \ \ (\text{stat}) \pm 0.5 \ \ (\text{syst})) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) = (-0.09 \pm 0.65\,(\text{stat}) \pm 0.48\,(\text{syst})) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.05 \pm 0.42\,(\text{stat}) \pm 0.29\,(\text{syst})) \times 10^{-3}$$

Run 2
($3.8\ \text{fb}^{-1}$)



No CP violation observed

Measurement of ΔA_{CP}

ΔA_{CP} status

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+)$$

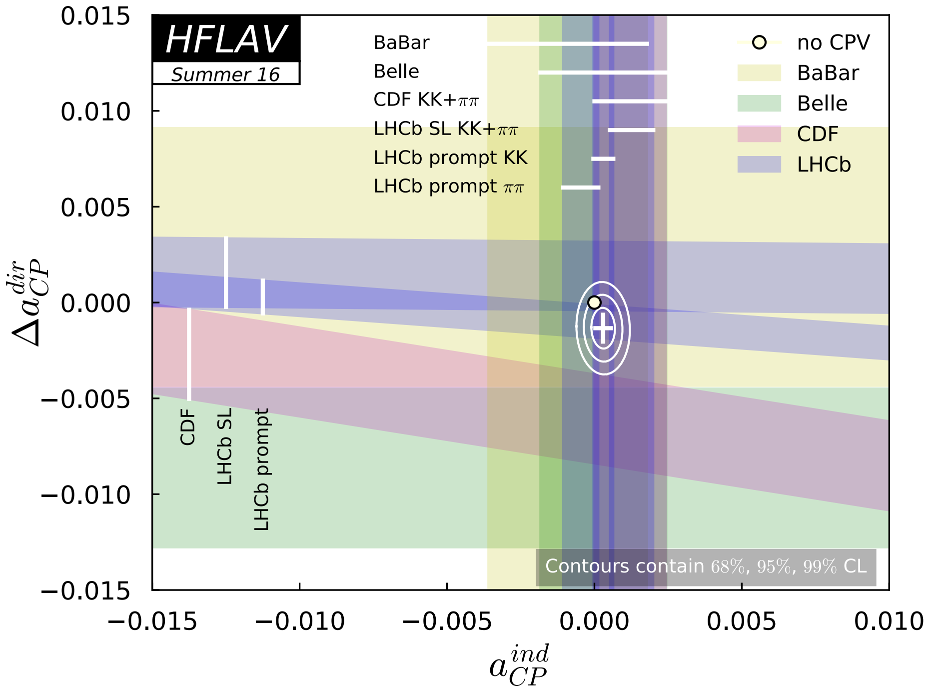
$$\simeq \Delta a_{CP}^{\text{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau(D^0)} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{\text{ind}}$$

Assumption: a_{CP} in decay/mixing interference is universal

$\overline{\langle t \rangle} = (\langle t \rangle_{KK} + \langle t \rangle_{\pi\pi})/2$

$\Delta t = \langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}$

- $\boldsymbol{a_{CP}^{\text{ind}}}$ mainly constrained by measurements of A_Γ
- ΔA_{CP} mostly sensitive to $\boldsymbol{\Delta a_{CP}^{\text{dir}}}$



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$$\simeq \Delta a_{CP}^{\mathrm{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau(D^0)} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{\mathrm{ind}}$$

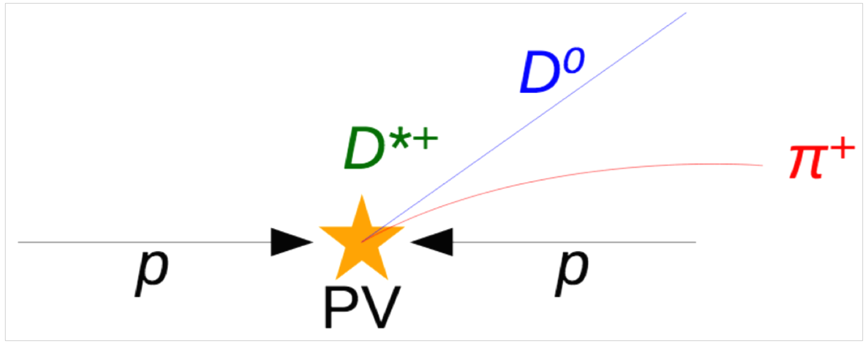
Assumption: a_{CP} in decay/mixing interference is universal

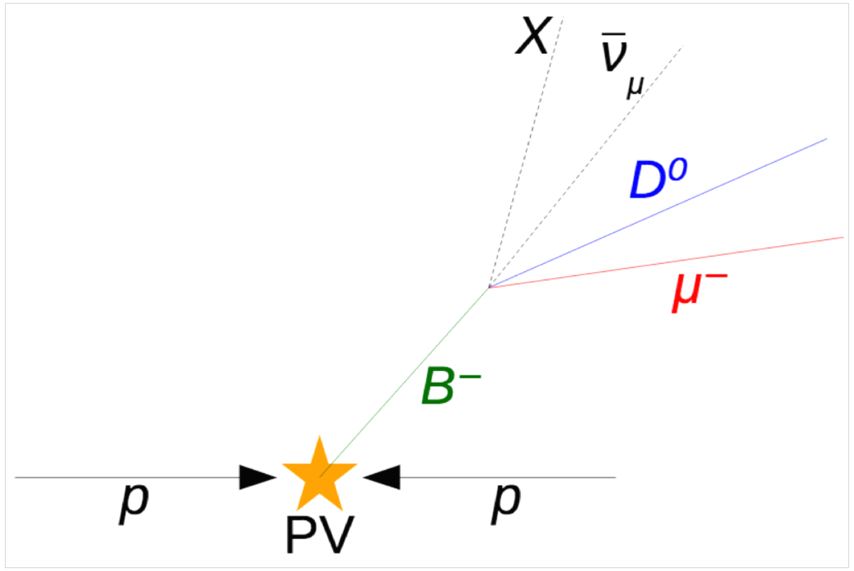
Experiment	ΔA_{CP}	
CDF	$(-62 \pm 21 \pm 10) \times 10^{-4}$	PRL 109 (2012) 111801
BaBar	$(+24 \pm 62 \pm 26) \times 10^{-4}$	PRL 100 (2008) 061803
Belle	$(-87 \pm 41 \pm 6) \times 10^{-4}$	arXiv:1212.1975
LHCb ($3.0\ \mathrm{fb}^{-1}$, muon-tagged)	$(+14 \pm 16 \pm 8) \times 10^{-4}$	JHEP 07 (2014) 041
LHCb ($3.0\ \mathrm{fb}^{-1}$, pion-tagged)	$(-10 \pm 8 \pm 3) \times 10^{-4}$	PRL 116 (2016) 191601

- Most **precise** measurements performed by LHCb with Run 1 data
- Today: **NEW** measurement with **full Run 2 ($6\ \mathrm{fb}^{-1}$)**

Flavour tagging

- Look at the **charge** of the accompanying particle
- **Prompt** charm: $D^{*\pm} \to D^0\pi^\pm$
  - D^0 points to PV
  - Decay time acceptance
- **Semileptonic** charm: $B \to D^0\mu^\pm X$
  - D^0 does not point to PV
  - Access all D^0 decay times
  - Lower yield





Strategy – Prompt tag

NEW

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$$A_{\rm raw}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)}$$

$D^{*+} \to D^0(\to K^+K^-)\pi_s^+$	$D^{*+} \to D^0(\to \pi^+\pi^-)\pi_s^+$

Valid up to $\mathcal{O}(10^{-6})$

$$A_{\rm raw}(f) \simeq A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_s) + A_{\rm P}(D^{*+})$$

- $A_{CP}(f)$: Physical *CP* asymmetry
- $A_{\rm D}(f)$: D^0 detection asymmetry ➔ equal to 0, since K^-K^+ and $\pi^-\pi^+$ are symmetric final states
- $A_{\rm D}(\pi_s)$: π_s detection asymmetry → Independent on the final state
- $A_{\rm P}(D^{*+})$: D^* production asymmetry → Independent on the final state

If the **kinematics** of the D^{*+} and π_s for the two decay modes are equal

$$\Rightarrow A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+)$$

Strategy – SL tag

NEW

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$$A_{\rm raw}(f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}$$

$\bar{B} \to D^0(\to K^+K^-)\mu^- X$	$\bar{B} \to D^0(\to \pi^+\pi^-)\mu^- X$

Valid up to $\mathcal{O}(10^{-6})$

$$A_{\rm raw}(f) \simeq A_{CP}(f) + A_{\rm D}(f) + A_D(\mu^-) + A_P(\bar{B})$$

- $A_{CP}(f)$: Physical *CP* asymmetry
- $A_{\rm D}(f)$: D^0 detection asymmetry ➔ equal to 0, since K^-K^+ and $\pi^-\pi^+$ are symmetric final states
- $A_D(\mu^-)$: μ^- detection asymmetry → Independent on the final state
- $A_P(\bar{B})$: $\bar{B}$ production asymmetry → Independent on the final state

If the **kinematics** of the $\bar{B}$ and μ^- for the two decay modes are equal

$$\Rightarrow A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+)$$

Selection

NEW

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- Reconstruction performed online (**Turbo** stream)

Comput. Phys. Commun. 208 (2016) 35

- **Requirements** placed on:
  - Quality and PID information of tracks
  - p_{T} of tracks and D^0
  - D^0 vertex quality
  - IP of D^0
  - $m_{corr} = \sqrt{m(D^0\mu) + p_T'(D^0\mu)} + p_T'(D^0\mu)$ for SL
  - $m(D^0)$ for prompt and $m(D^0\mu)$ for SL
- SL candidates are further filtered with a **MVA** using as input the quality of the vertices, the D^0 flight distance, the IP and p_{T} of the D^0 decay products

Fiducial selection

NEW

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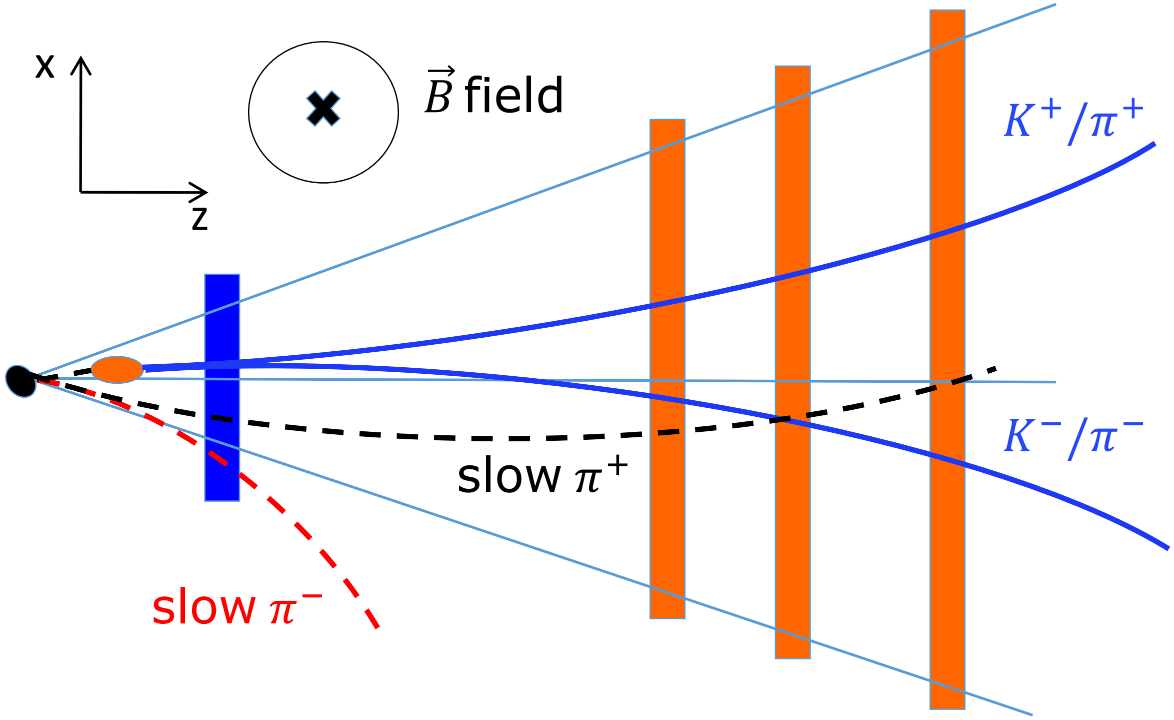
- For some regions of phase space, the soft pion of a specific charge is **kicked out** from the detector acceptance by the magnetic field
- In such regions very large values of the raw asymmetries are found



Fiducial selection

NEW

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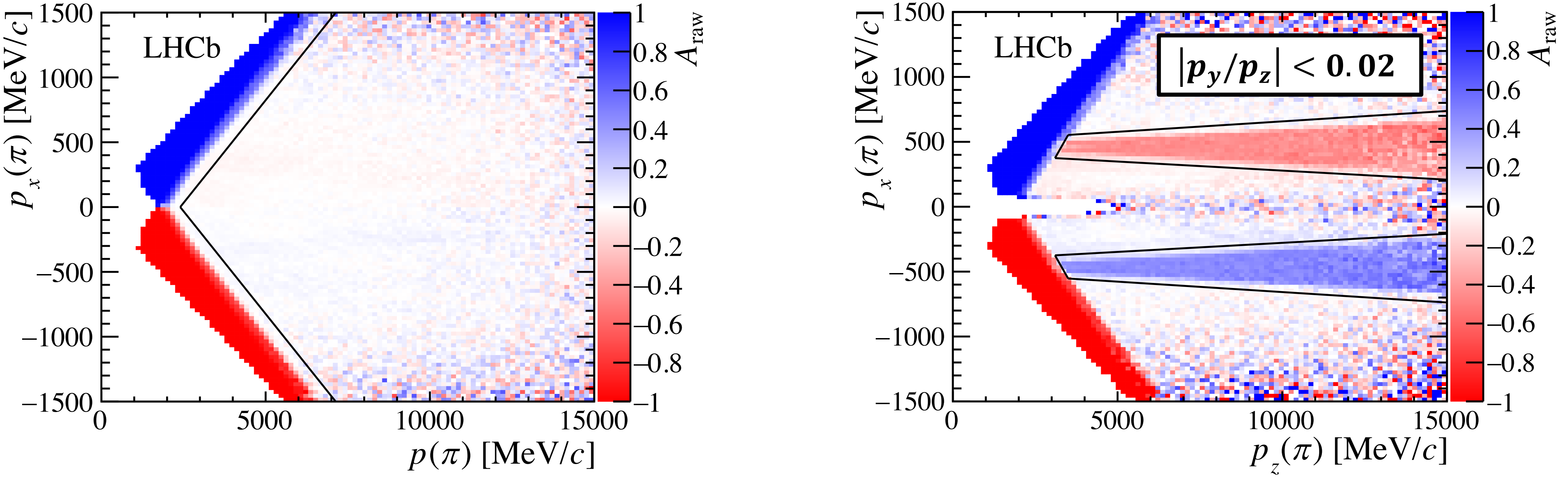
- Remove soft pion kinematic regions when the **raw asymmetry is very high**
- Similarly for the muon in the SL sample



Kinematic weighting

NEW

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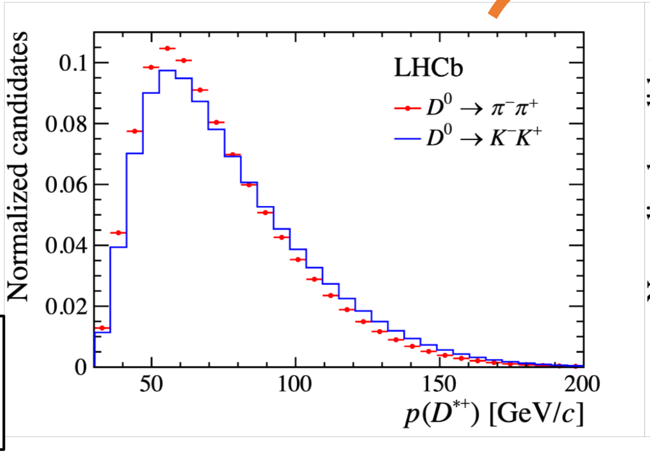
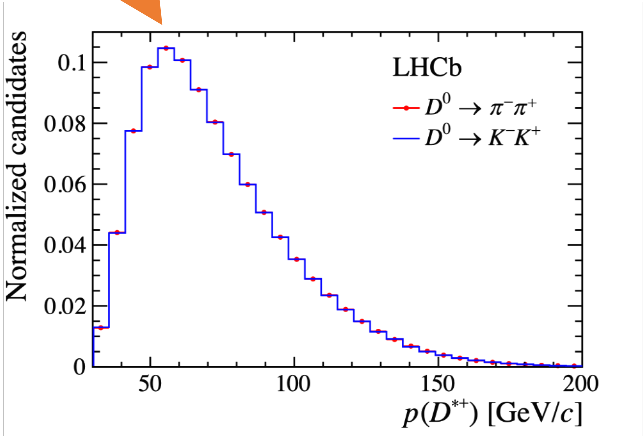
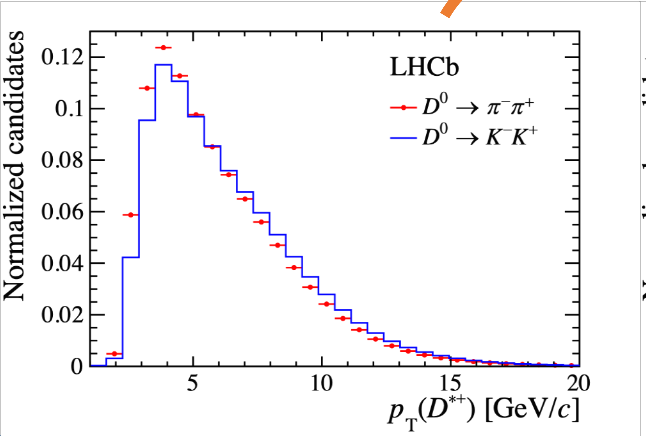
Weight KK to $\pi\pi$ kinematics:

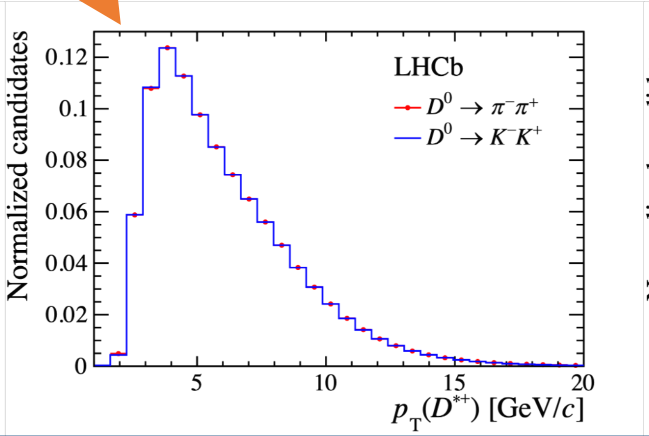
- **Prompt**: $p_T(D^*)$, $p(D^*)$, $\phi(D^*)$
- **SL**: $p_T(D^0)$, $p(D^0)$, $\phi(D^0)$

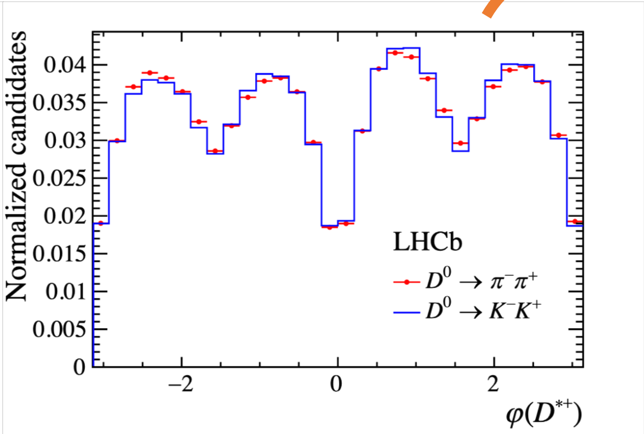
Very small change on ΔA_{CP}

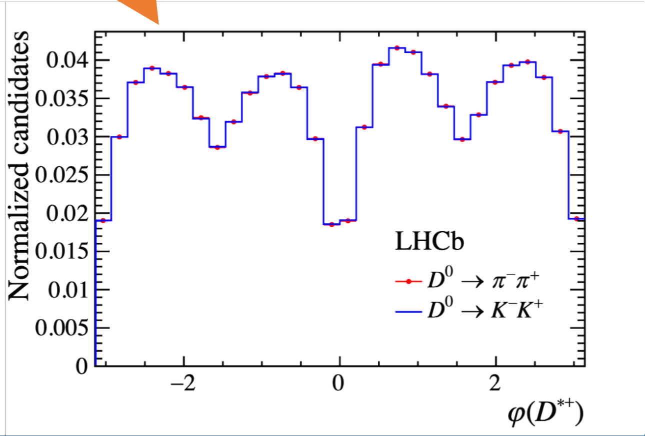












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LHCb-PAPER-2019-006

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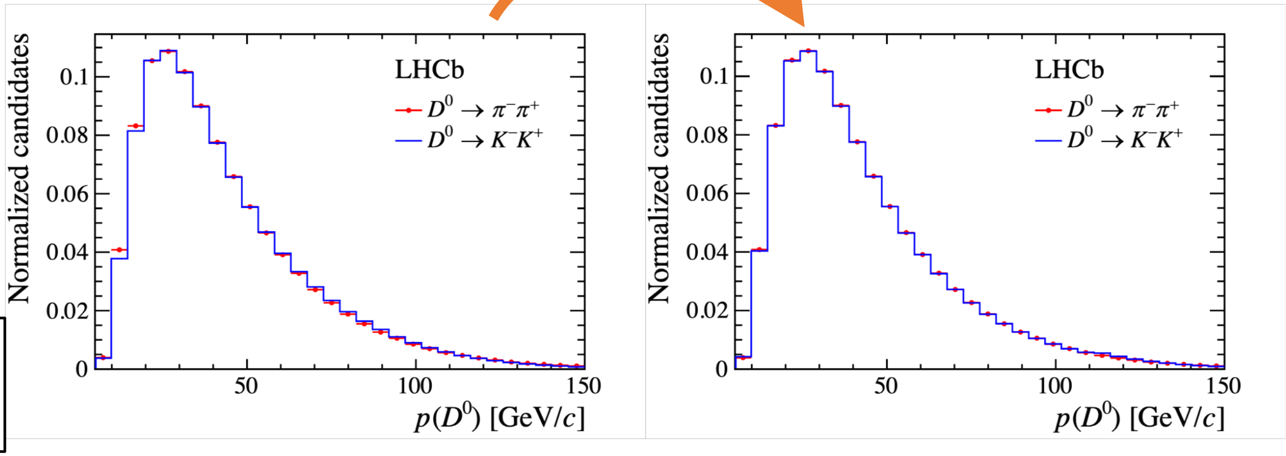

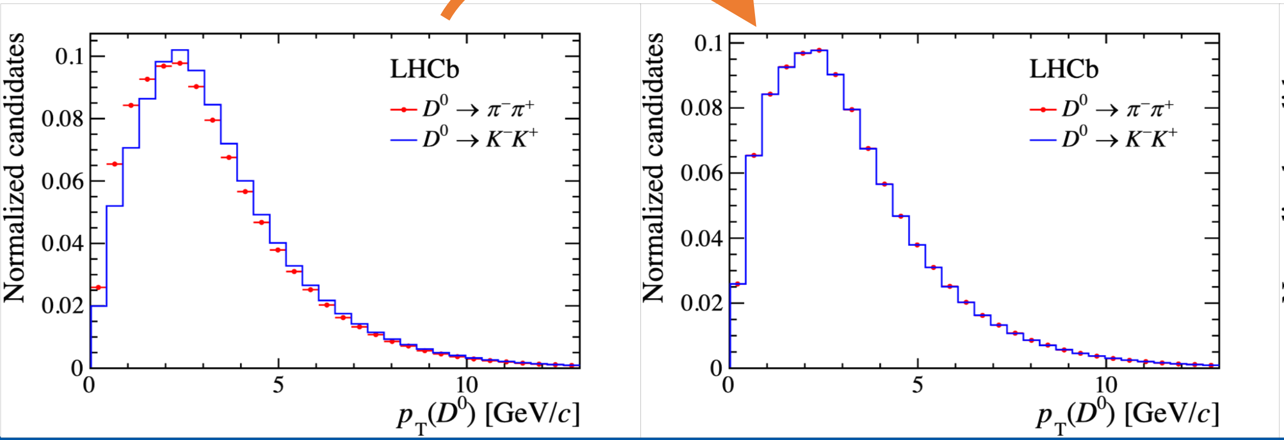

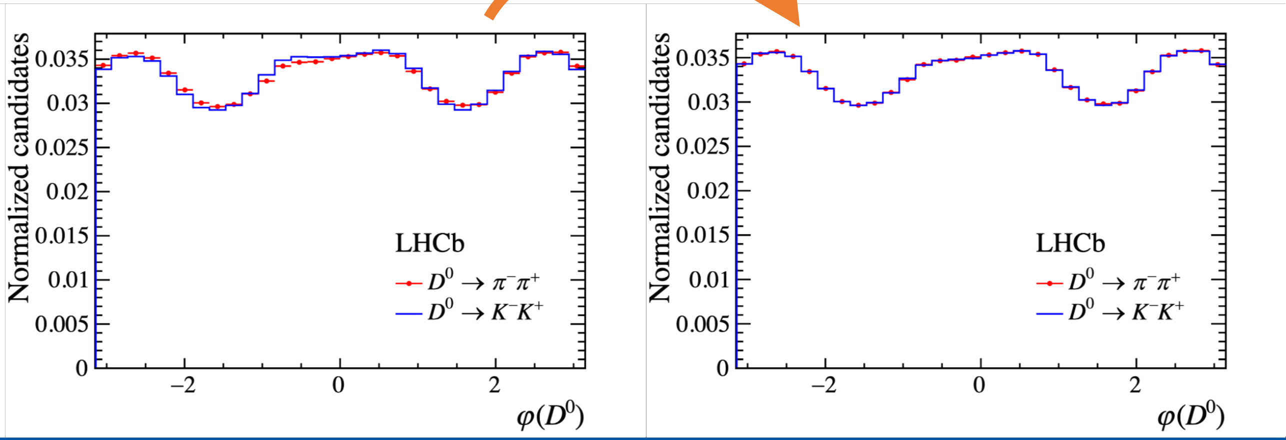

A_{raw} measurement

NEW

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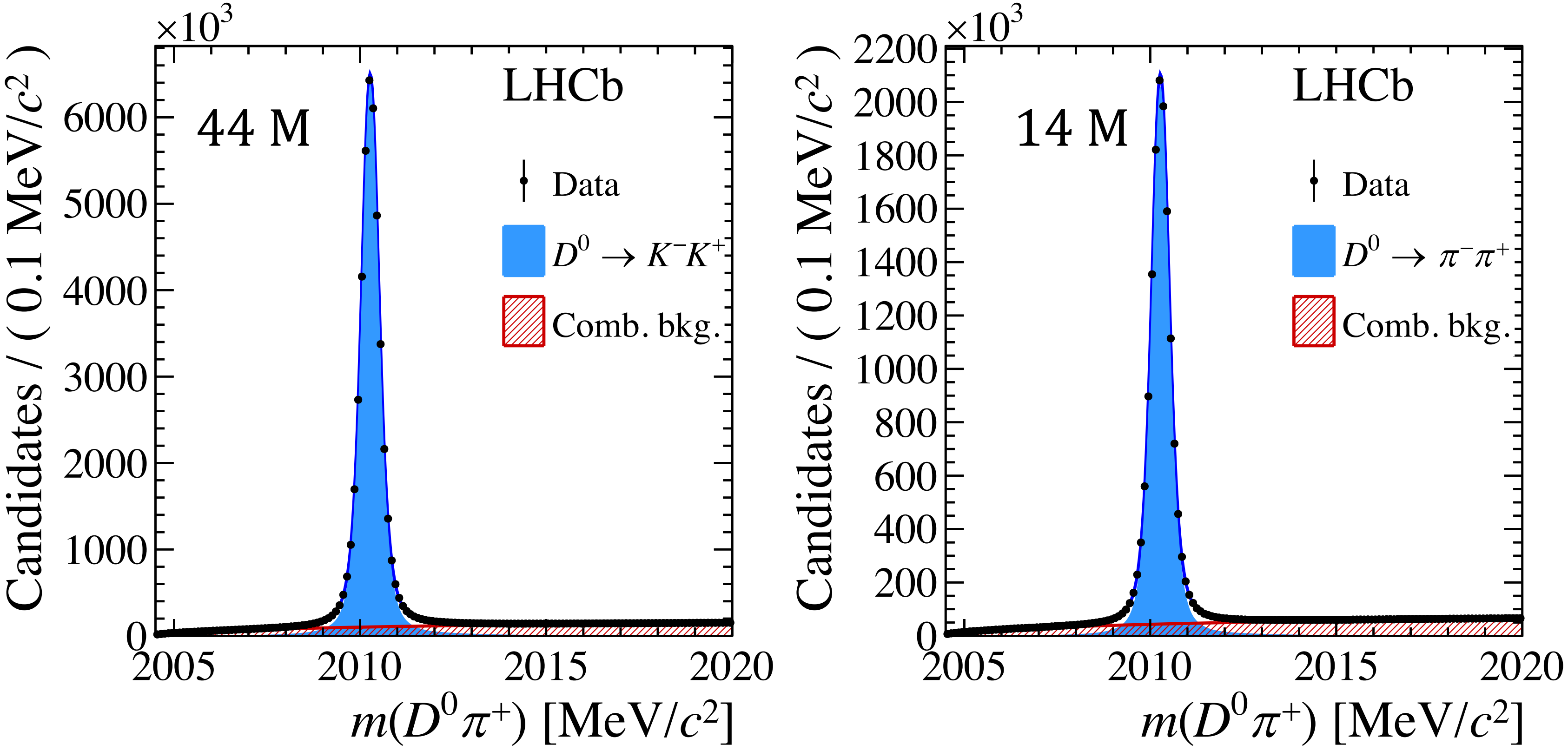
PROMPT

- Fit $\boldsymbol{m(D^0\pi)}$ distribution
- $\boldsymbol{A_{\mathrm{raw}}}$ **parameter** of the fit shared between D^{*+} and D^{*-}
- About **44 million** signal decays for K^-K^+ and **14 million** for $\pi^-\pi^+$



A_{raw} measurement

NEW

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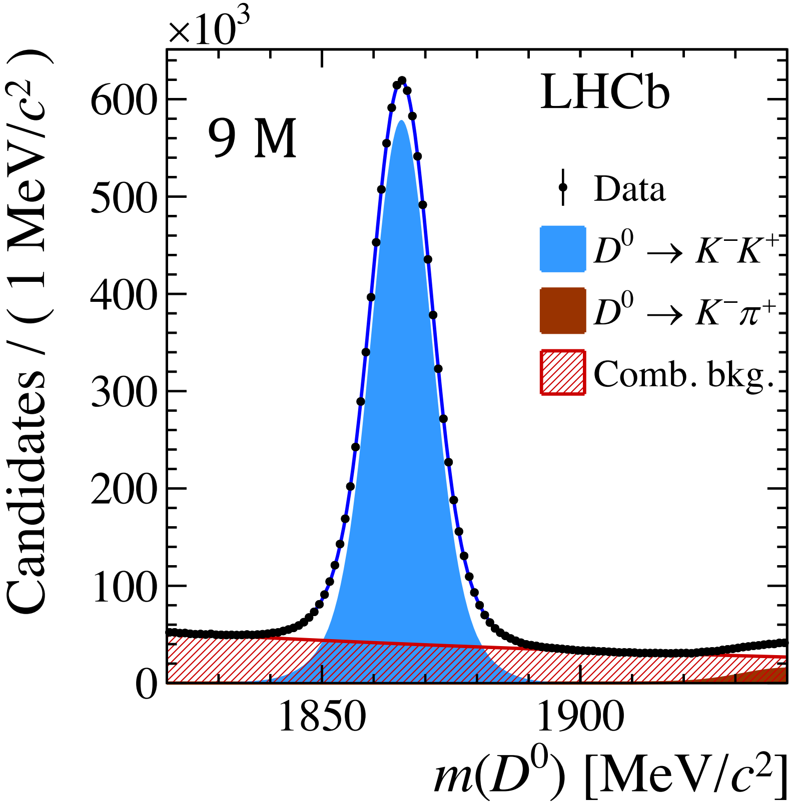
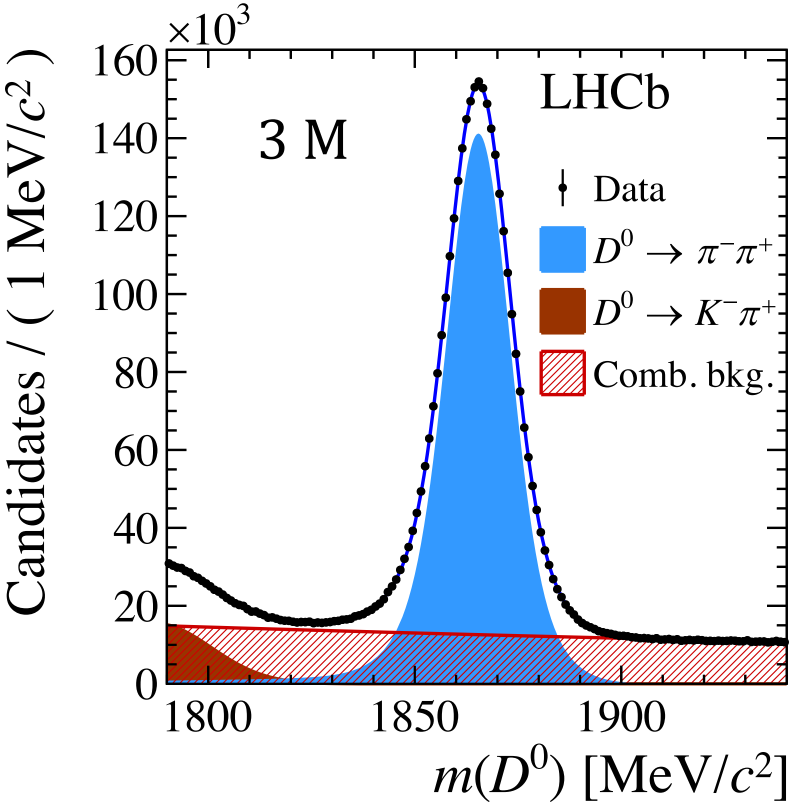
SL

- Fit $\boldsymbol{m(D^0)}$ distribution
- $\boldsymbol{A_{\text{raw}}}$ **parameter** of the fit shared between D^0 and $\bar{D}^0$
- About **9 million** signal events for K^-K^+ and **3 million** for $\pi^-\pi^+$





Systematic uncertainties

NEW

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- **Prompt** dominated by:
  - **Fit model** → evaluated by fitting pseudoexperiments with alternative models
  - **Misreconstructed background** ($D^0 \to K^-\pi^+\pi^0$, $D^0 \to \pi^- l^+ \nu_l$) peaking in $m(D^0\pi)$ → estimated by measuring the yields and asymmetries of backgrounds on the $m(D^0)$ distributions

Source	π-tagged $[10^{-4}]$	μ-tagged $[10^{-4}]$
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B^0 fraction	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

- **SL** dominated by **mistag** (wrong muon) → evaluated on the $B \to D^0(\to K^-\pi^+)\mu X$ control sample

Stability

NEW

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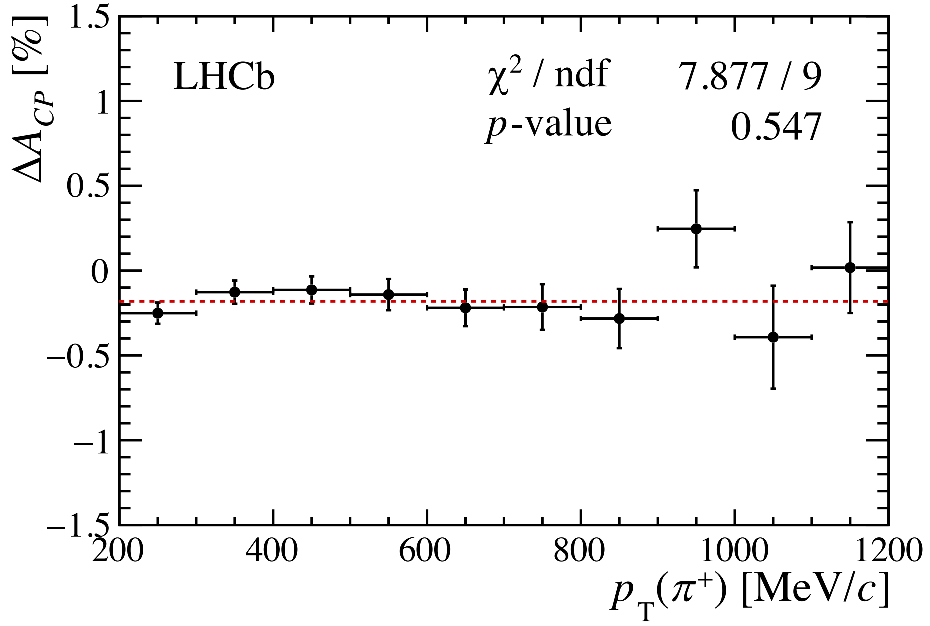
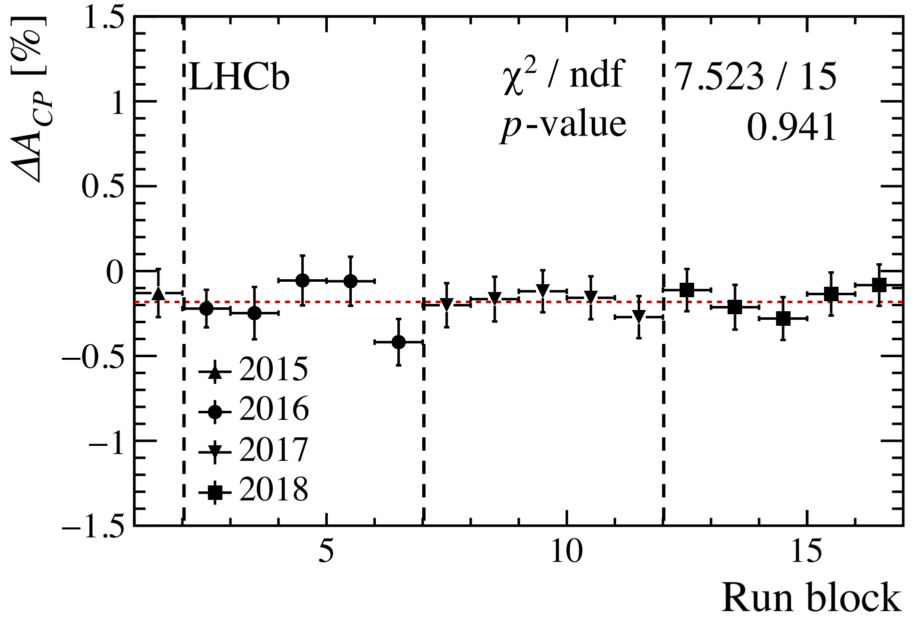
- Sample split according to **year** and magnet **polarity**
- ΔA_{CP} measured as a function of various **kinematic/geometrical**
- Alternative **selections** (*e.g.* tighter PID) tested

➔ No evidence for unexpected dependencies are seen



PROMPT



Results

NEW

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$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

- Compatible with **previous** LHCb results and the **WA**

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- Compatible with **previous** LHCb results and the **WA**
- **Combination** with LHCb Run 1 gives:

$$\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9)\times 10^{-4}}$$

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CP violation observed at $\boldsymbol{5.3\sigma}$!!

Interpretation

NEW

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- For the **interpretation**, $\Delta\langle t\rangle/\tau(D^0)$ and $\overline{\langle t\rangle}/\tau(D^0)$ are needed
- For the full LHCb data set ($\mathbf{9fb^{-1}}$):

$$\boldsymbol{\Delta\langle t\rangle/\tau(D^0) = 0.115 \pm 0.002,\ \overline{\langle t\rangle}/\tau(D^0) = 1.71 \pm 0.10}$$

- Using the LHCb averages:
  - $y_{CP} = (5.7 \pm 1.5)\times10^{-3}$
  - $A_\Gamma = (-2.8 \pm 2.8)\times10^{-4} \simeq -a_{CP}^{\text{ind}}$

$$\Delta A_{CP} \simeq \Delta a_{CP}^{\text{dir}}\left(1 + \frac{\overline{\langle t\rangle}}{\tau(D^0)} y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau(D^0)} a_{CP}^{\text{ind}}$$

$$\boldsymbol{\Delta a_{CP}^{\text{dir}} = (-15.6 \pm 2.9)\times10^{-4}}$$

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$$\boldsymbol{\Delta a_{CP}^{\text{dir}} = (-15.6 \pm 2.9)\times 10^{-4}}$$

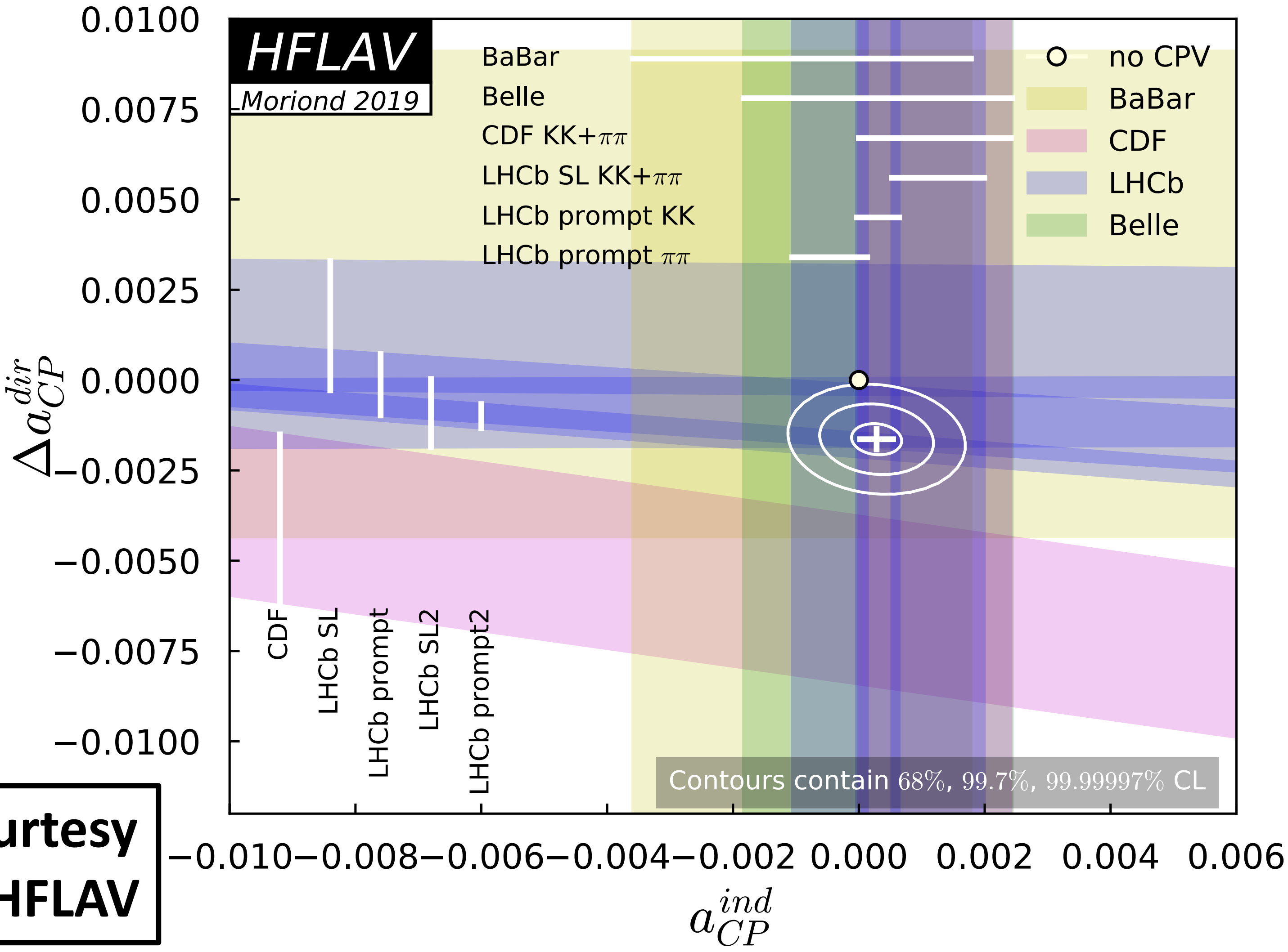
ΔA_{CP} mostly sensitive to direct *CP* violation

New World Average

Including new y_{CP} and ΔA_{CP} measurements:

$$\Delta a_{CP}^{\text{dir}} = (-16.4 \pm 2.8)\times 10^{-4}$$
$$a_{CP}^{\text{ind}} = (2.8 \pm 2.6)\times 10^{-4}$$

Consistency with NO CPV hypothesis: 5.4×10^{-8} (5.44σ)



Courtesy of HFLAV

Comparison with the SM

- The result is **consistent** with, although at the **upper end** of, SM **expectations**, which lie in the range $10^{-4} - 10^{-3}$

PLB 222 (1989) 501
PRD 51 (1995) 3478
Riv. Nuovo Cim. 26N7 (2003) 1
PRD 75 (2007) 036008
Ann. Rev. Nucl. Part. Sci. 58 (2008) 249
PLB 774 (2017) 235
… and many others

- **Further measurements** with charmed particles, along with possible **theoretical improvements**, will help clarify the physics picture
  ➔ establish whether this result is consistent with the **SM** or indicates the presence of **new dynamics** in the up-quark sector

Conclusions

- New LHCb measurements of:
  - y_{CP} and x_{CP} (Run 1): $x > 0$ at more than 3σ
  - A_{CP} in $D_s^+ \to K_s^0 \pi^+$, $D^+ \to K_s^0 K^+$, $D^+ \to \phi\pi^+$ (Run 2)

→ no CP violation in D^0 mixing nor in $D_{(s)}^+$ decays

- New measurement of ΔA_{CP} with full LHCb Run 2 presented today for the first time → $\Delta A_{CP} \neq 0$ at more than 5σ

_CP_ VIOLATION IN CHARM HADRON DECAYS OBSERVED FOR THE FIRST TIME

Backup slides

$A_{CP}(K^-K^+)$ and $A_{CP}(\pi^-\pi^+)$

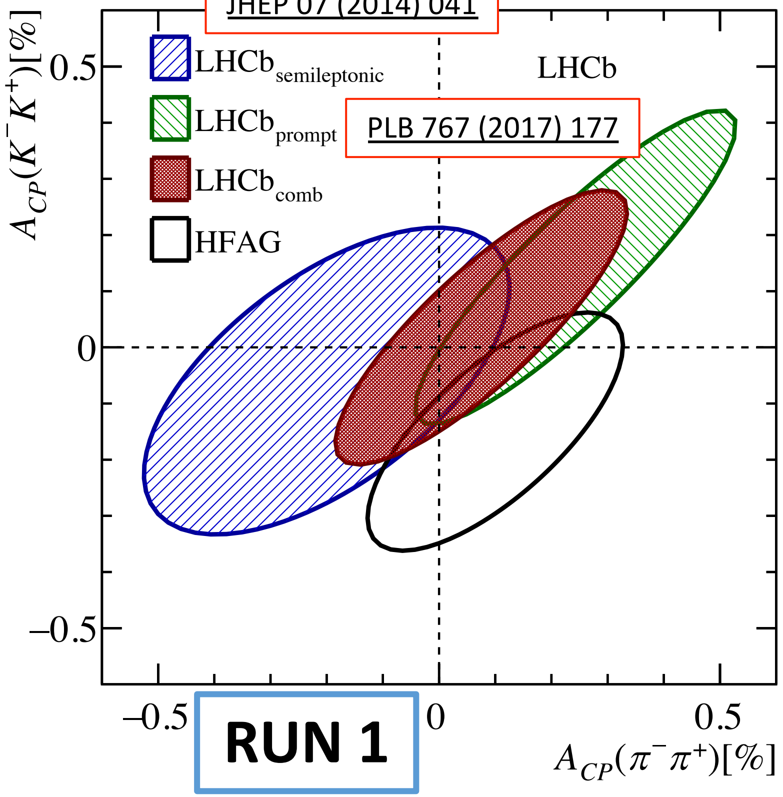
$$A_{CP}(K^-K^+) = A_{\text{raw}}(K^-K^+) - A_{\text{raw}}(K^-\pi^+) + A_{\text{D}}(K^-\pi^+)$$

$$A_{\text{D}}(K^-\pi^+) = A_{\text{raw}}(K^-\pi^+\pi^+) - A_{\text{raw}}(\bar{K}^0\pi^+) + A_{\text{D}}(\bar{K}^0)$$

- $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \bar{K}^0\pi^+$ **control samples** are needed
- **Trickier** than ΔA_{CP}, weighting is not simple and systematic associated to PID asymmetry must be carefully evaluated
- **Work already started** to measure $A_{CP}(h^-h^+)$ on the full **Run 1 + Run 2**

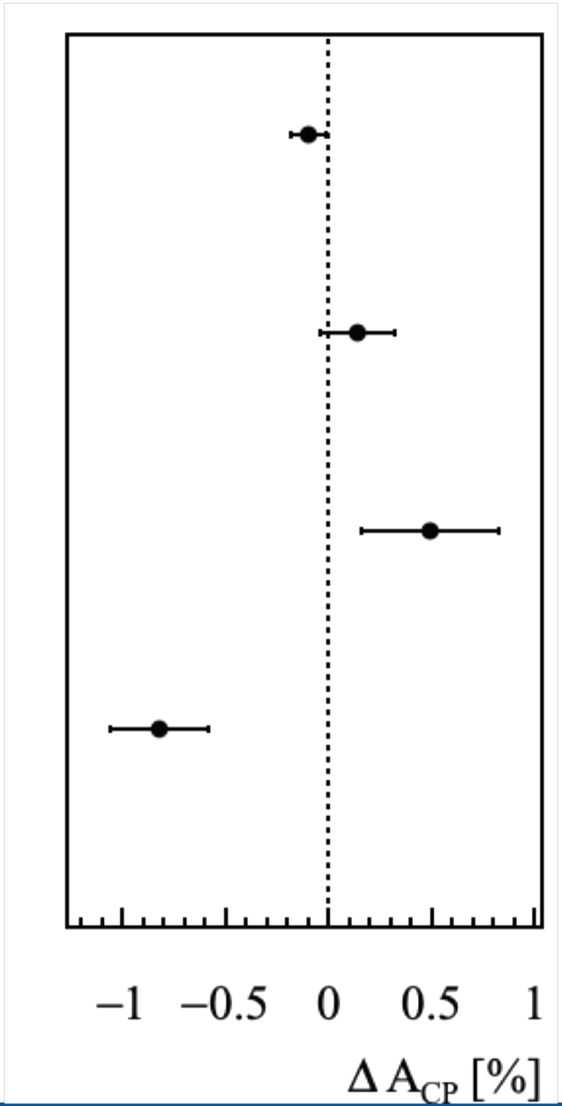
JHEP 07 (2014) 041

PLB 767 (2017) 177



$A_{CP}(K^-K^+) = (0.04 \pm 0.12 \pm 0.10)\%$
$A_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14 \pm 0.11)\%$

ΔA_{CP} at LHCb – History



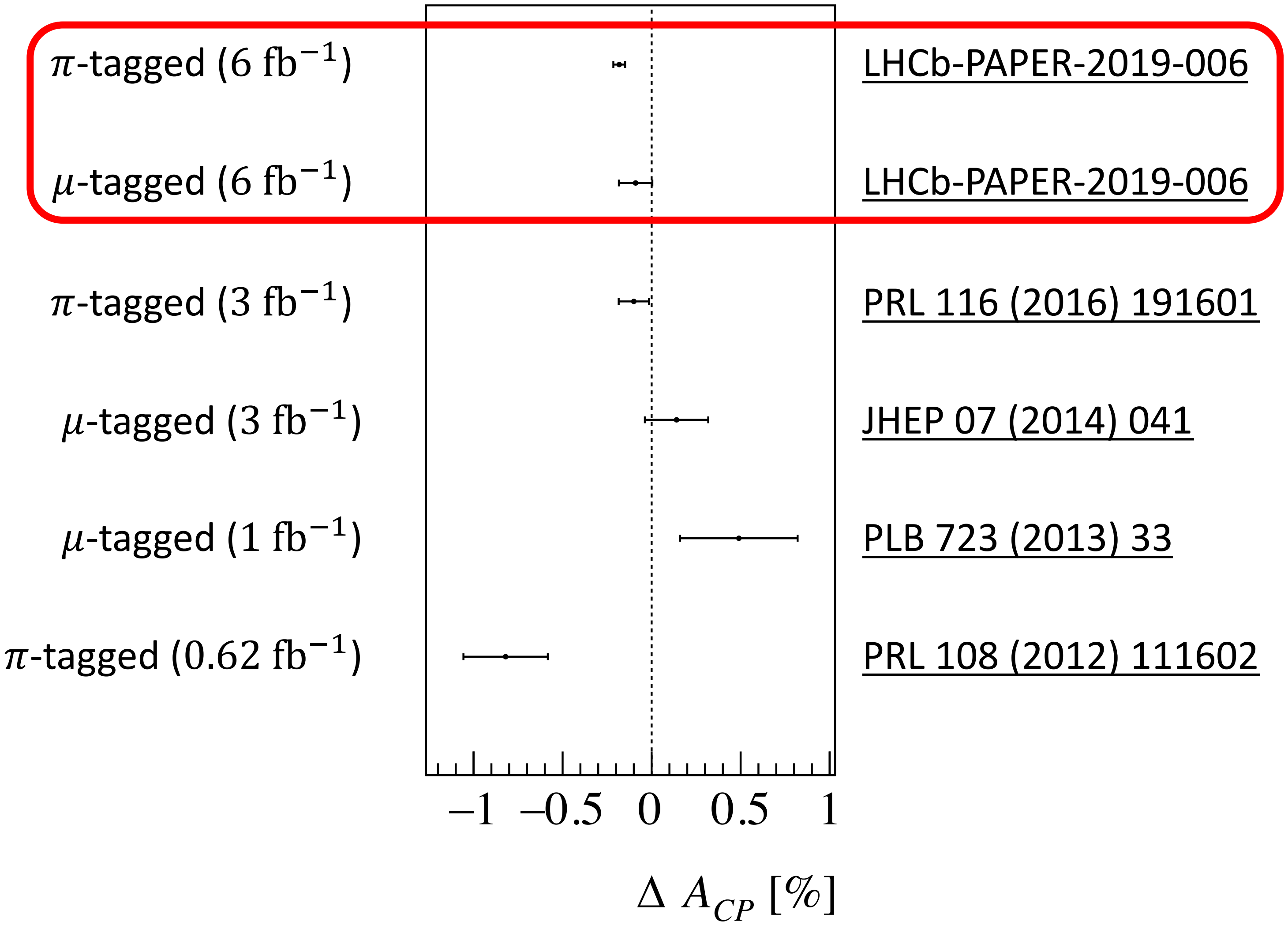
π-tagged (3 fb^{-1}) — PRL 116 (2016) 191601

μ-tagged (3 fb^{-1}) — JHEP 07 (2014) 041

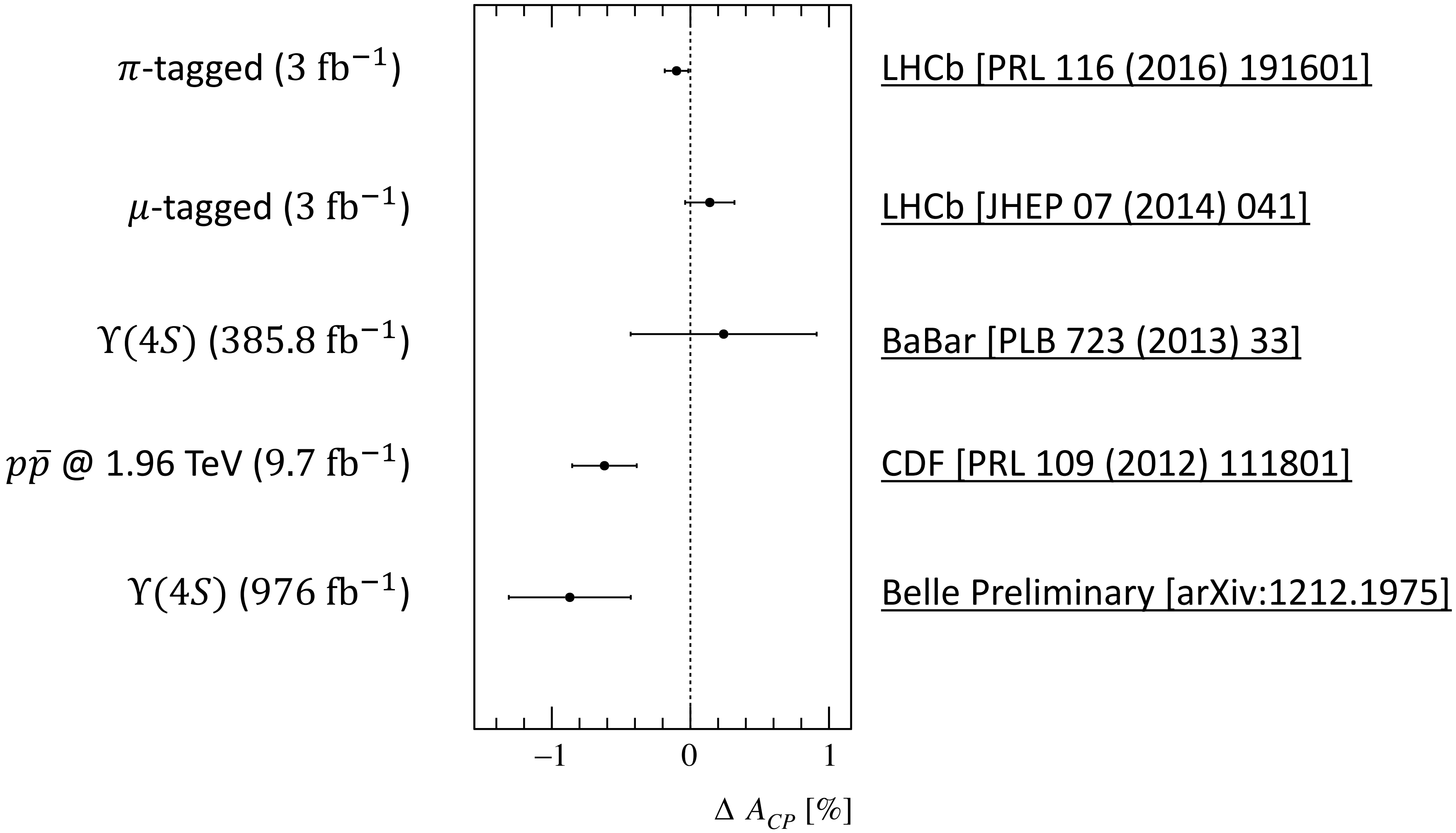
μ-tagged (1 fb^{-1}) — PLB 723 (2013) 33

π-tagged (0.62 fb^{-1}) — PRL 108 (2012) 111602

ΔA_{CP} at LHCb – History + Run 2



ΔA_{CP} – History



ΔA_{CP} – Future prospects

LHCB-PUB-2018-009

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^- K^+$	Yield $D^0 \to \pi^- \pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

- With Upgrade-I $\sigma_{stat}(\Delta A_{CP})$ expected to be $\mathcal{O}(10^{-4})$
- $\sigma_{stat}(\Delta A_{CP}) \sim 3\times10^{-5}$ including Run 5 (Upgrade-II)

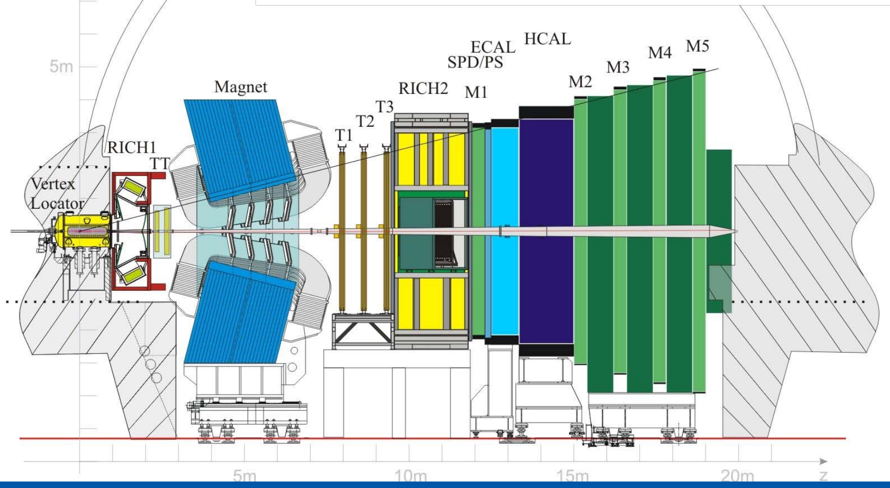
Charm at LHCb

- Large $c\bar{c}$ production cross section
  $\sigma(pp \to c\bar{c}X)_{\sqrt{s}=13\ TeV} = (2369 \pm 3 \pm 152 \pm 118)\ \mu b$

JHEP 05 (2017) 074

$$\sigma(pp \to D^0 X) = 2072 \pm 2 \pm 124\ \mu b$$
$$\sigma(pp \to D^+ X) = 834 \pm 2 \pm 78\ \mu b$$
$$\sigma(pp \to D_s^+ X) = 353 \pm 9 \pm 76\ \mu b$$
$$\sigma(pp \to D^{*+} X) = 784 \pm 4 \pm 87\ \mu b$$

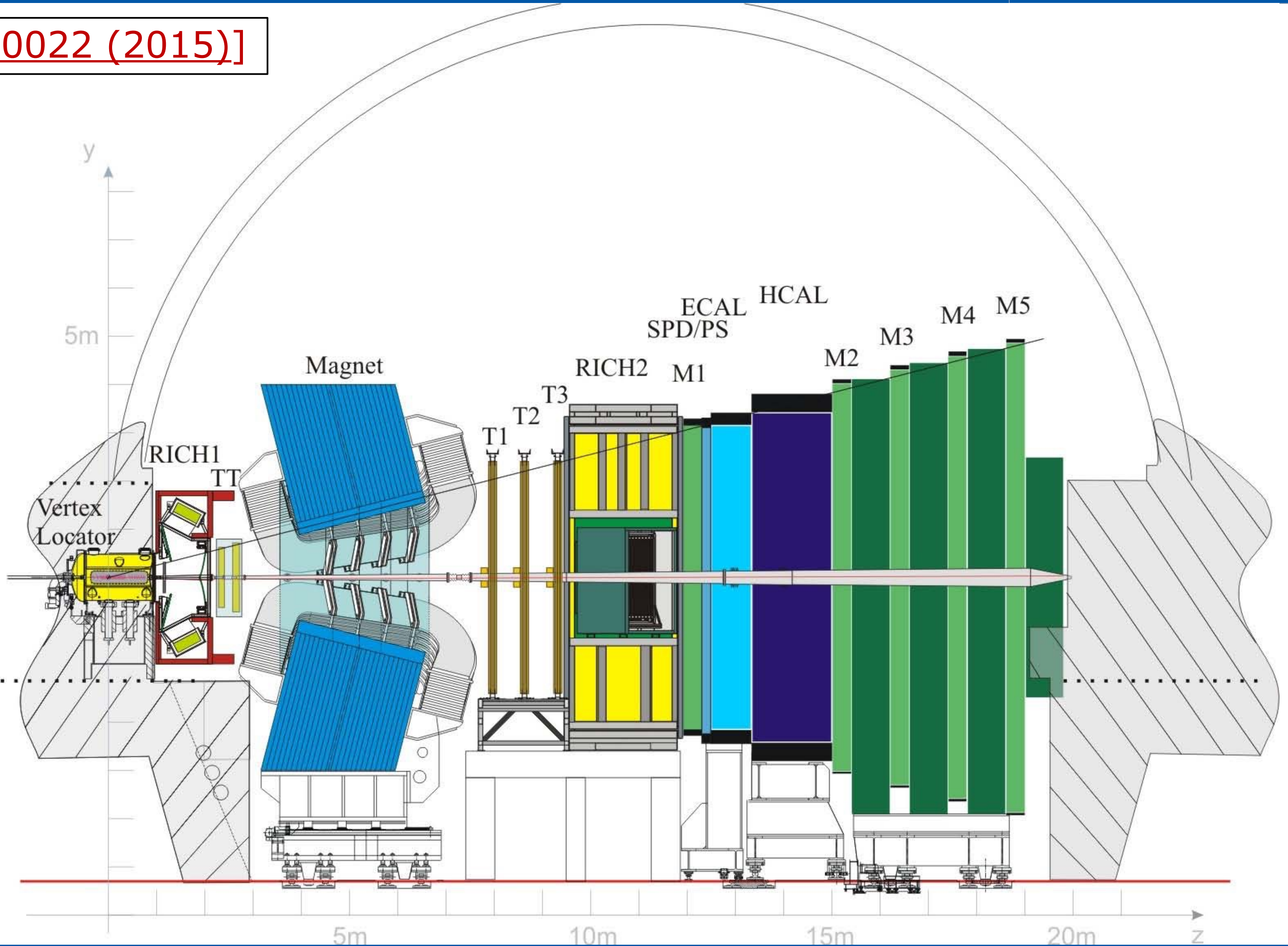
- More than 1 billion $D^0 \to K^-\pi^+$ decays reconstructed with the full LHCb data sample
- LHCb detector: JINST 3 (2008) S08005
  - Excellent **IP** resolution ($\sim$20 μm)
  - Very good **momentum** resolution ($\delta p/p \sim 0.5\%$)
  - Excellent **PID** capabilities



The LHCb detector

[Int. J. Mod. Phys. A 30, 1530022 (2015)]

- Single arm spectrometer in $2 < \eta < 5$ range
- Excellent **vertex** resolution ($13\ \mu m$ in transverse plane for primary vertex)
- Excellent **IP** resolution ($\sim 20\ \mu m$)
- Very good **momentum** resolution ($\delta p/p \sim 0.5\% - 0.8\%$)
- Excellent **PID** capabilities
- Very good **trigger** efficiency ($\sim 90\%$)

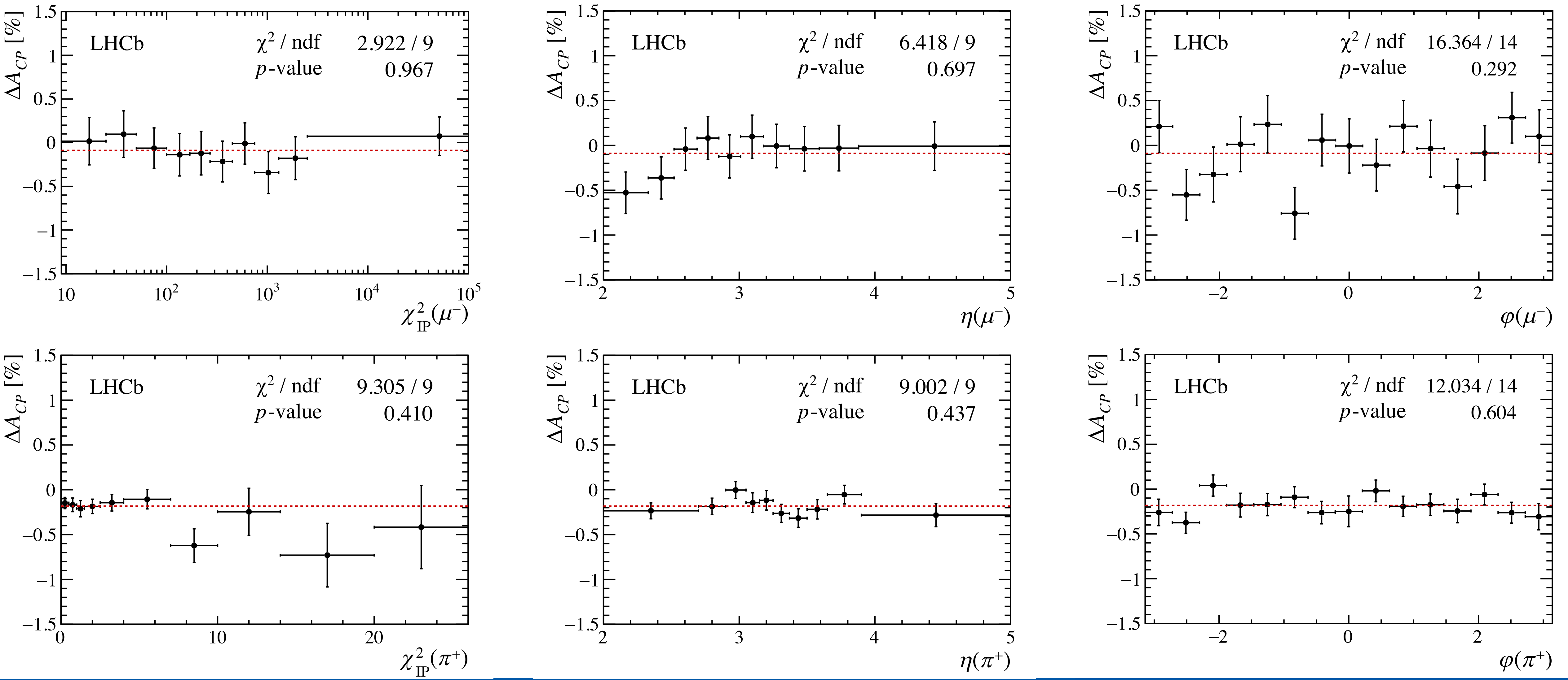


ΔA_{CP} – Fit model

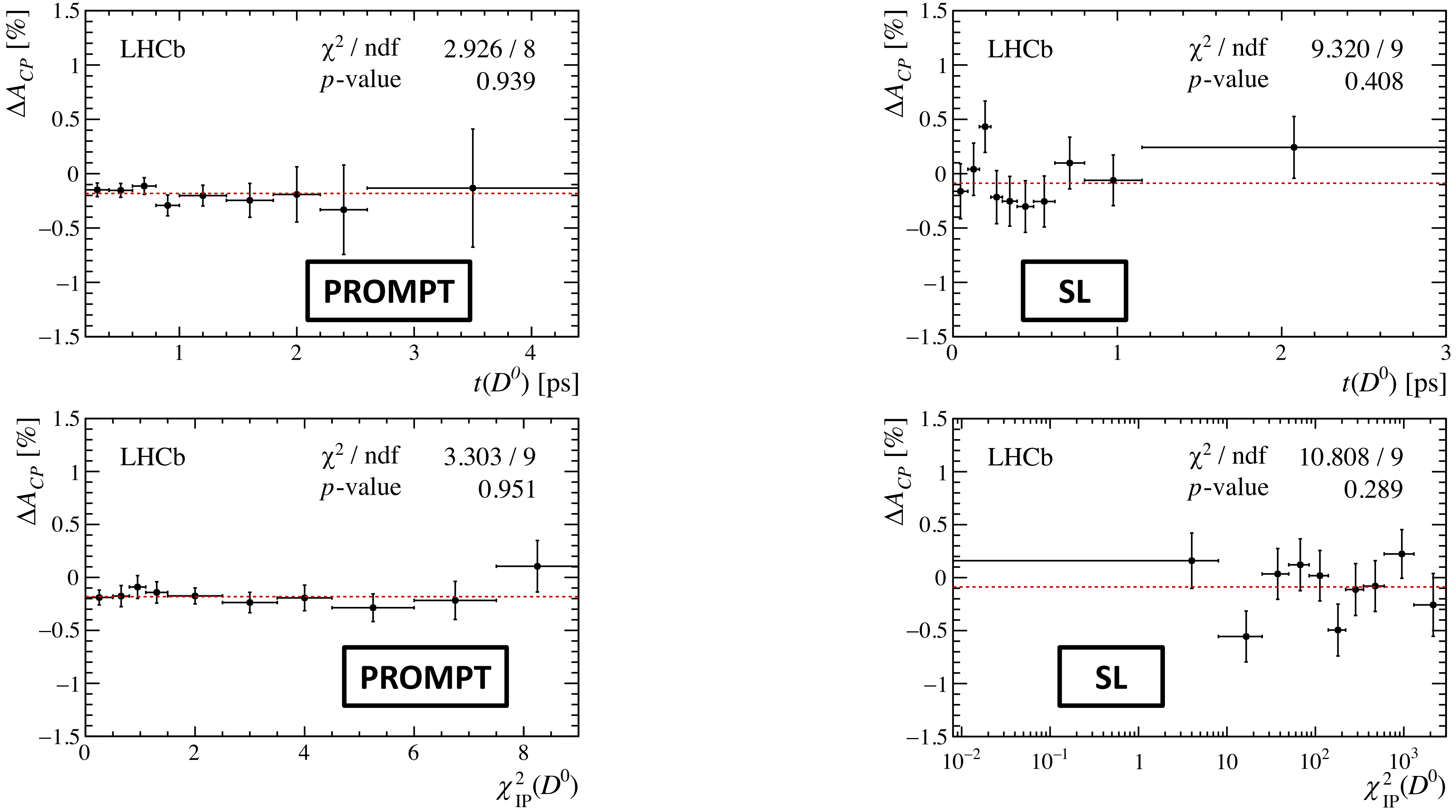
$$\mathcal{J}(m;\mu_J,\sigma_J,\delta_J,\gamma_J) = \frac{e^{-\frac{1}{2}\left[\gamma_J+\delta_J \sinh^{-1}\left(\frac{m-\mu_J}{\sigma_J}\right)\right]^2}}{\sqrt{1+\left(\frac{m-\mu_J}{\sigma_J}\right)^2}}$$

- Prompt case:
  - Signal: sum of three Gaussian and a Johnson SU
  - Background: empirical function $[m(D^0\pi^+) - m(D^0) - m(\pi^+)]^\alpha e^{\beta\, m(D^0\pi^+)}$
- Semileptonic case:
  - Signal: sum of two Gaussian functions convolved with a power-law function
  - Background: exponential function
  - misID $D^0 \to K^-\pi^+$: tail of a Gaussian

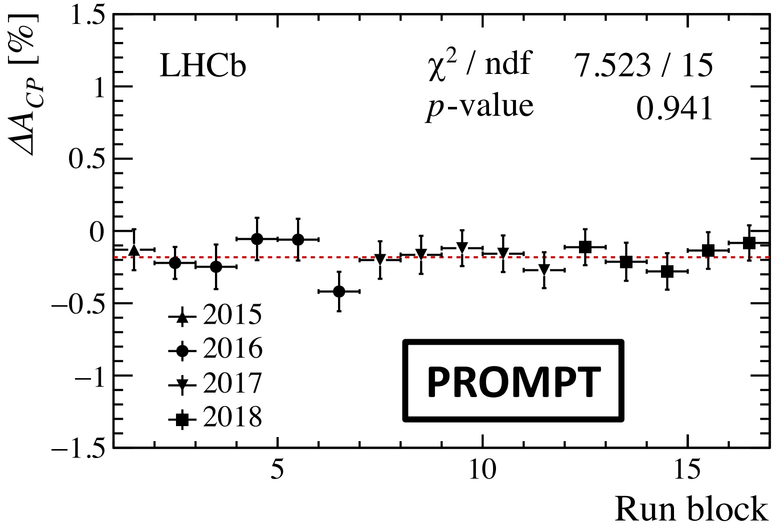
ΔA_{CP} – Stability

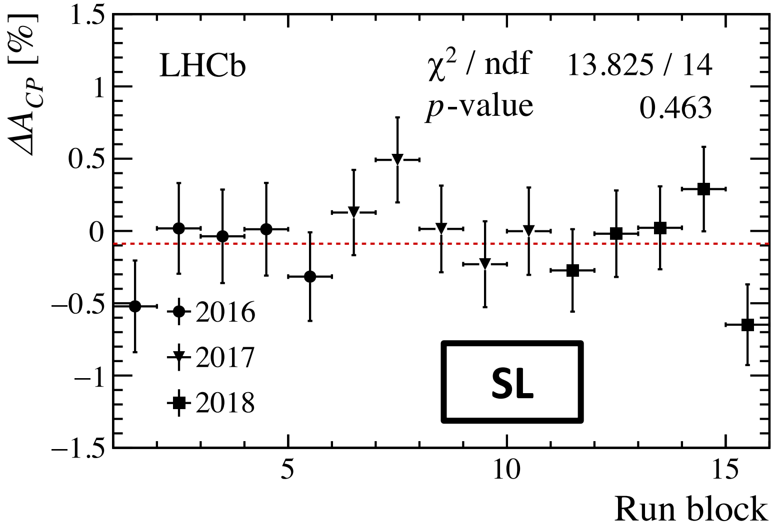


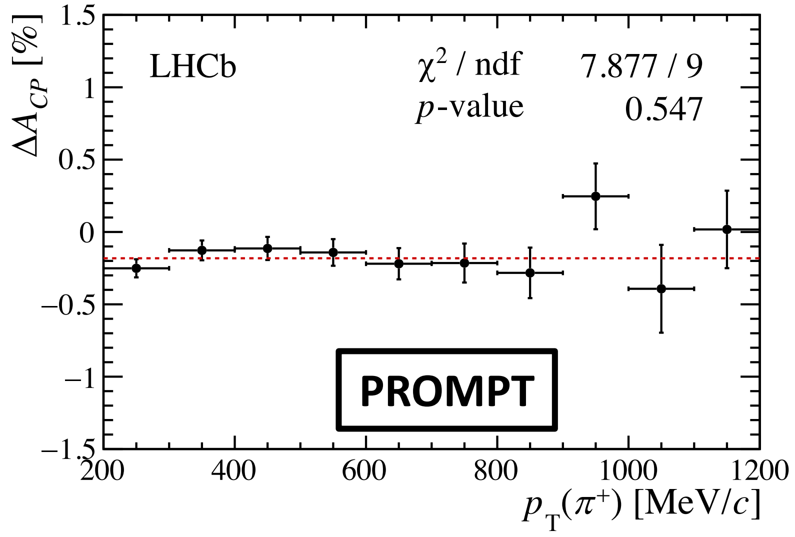
ΔA_{CP} – Stability

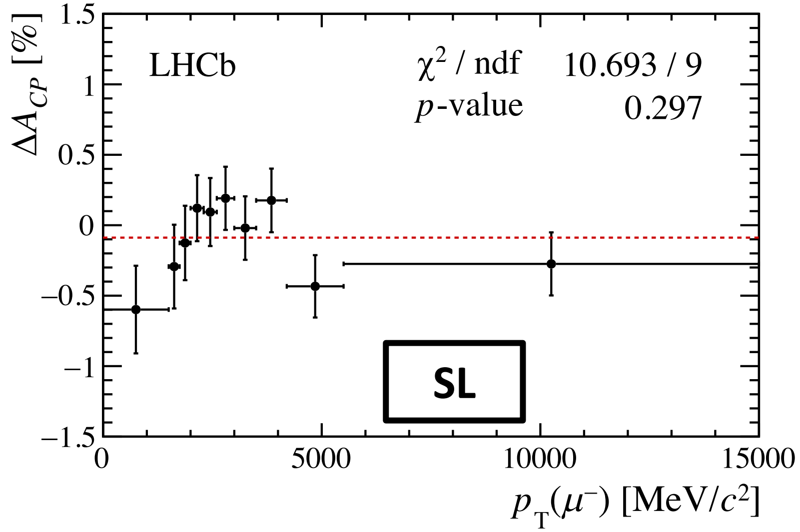


ΔA_{CP} – Stability









ΔA_{CP} – Cross-checks

- Found variations compatible with **statistical fluctuation** on ΔA_{CP} measured with:
  - Alternative PID cuts
  - Alternative fiducial cuts
  - Alternative hardware trigger categories
  - All multiple candidates kept (baseline is to keep only one)
- $\boldsymbol{\Delta A_{bkg}} = (-0.023 \pm 0.041)\%$ → compatible with 0 at $\mathbf{0.6\sigma}$
- ΔA_{CP} measured by **counting** events after sideband subtraction → differences well below the systematic uncertainty

ΔA_{CP} – Fit model systematic

- Choose 6 **alternative** fit models
- **1000 toys** for each subsample → generate with baseline → fit with baseline and alternative → calculate $\Delta A_{CP,alt} - \Delta A_{CP,nom}$
- **Sum in quadrature** mean and σ of $\Delta A_{CP,alt} - \Delta A_{CP,nom}$ distribution for each model
- As a conservative choice, take the maximum as systematic uncertainty

→ $\mathbf{0.6{\times}10^{-4}}$ for prompt and $\mathbf{2{\times}10^{-4}}$ for SL

ΔA_{CP} – Weighting systematic

- Uncertainty on weighting function due to **limited statistics**
- Gaussian extraction of **alternative weight** event by event → fit to get $\Delta A_{CP,alt}$
- Perform **300** tests
- Uncertainty is the sum in quadrature of mean and σ of $\Delta A_{CP,alt} - \Delta A_{CP,nom}$

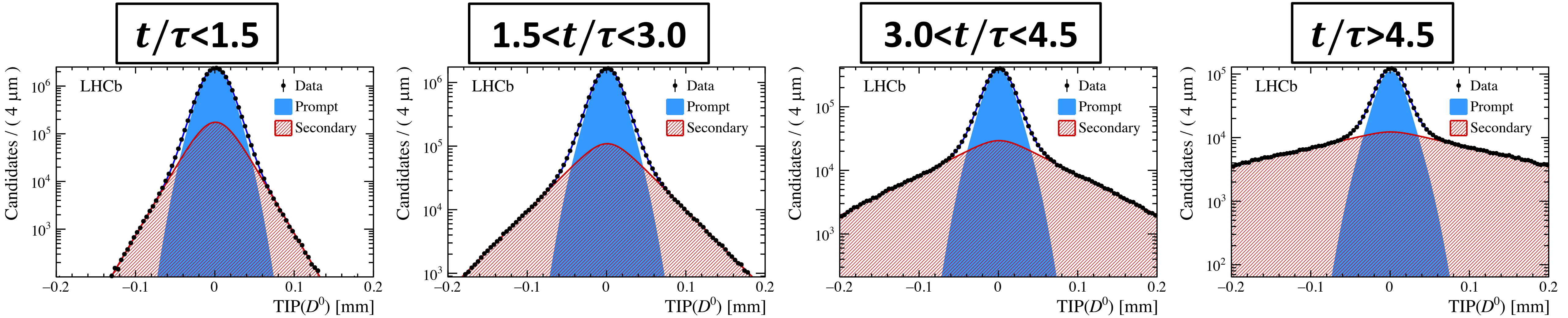
➔ $\mathbf{0.2{\times}10^{-4}}$ for prompt and $\mathbf{1{\times}10^{-4}}$ for SL

ΔA_{CP} – Secondaries (Prompt)

$$\Delta_{\text{sec}} = \frac{f_{\text{sec}}^{K^+K^-} - f_{\text{sec}}^{\pi^+\pi^-}}{2}\left[A_{\text{raw}}^{\text{sec}}(KK) + A_{\text{raw}}^{\text{sec}}(\pi\pi) - A_{\text{raw}}^{\text{prompt}}(KK) - A_{\text{raw}}^{\text{prompt}}(\pi\pi)\right]$$

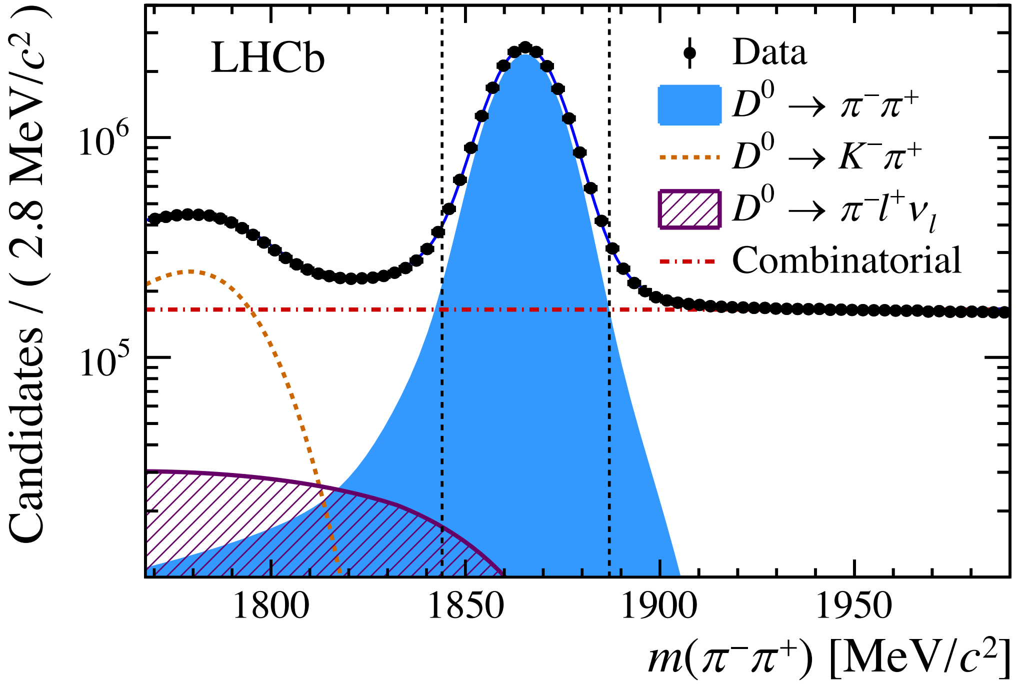
- Measure fraction of **secondary** D^0 by fitting the distribution of the D^0 IP in the plane transverse to the beam (**TIP**)
- Study performed in **bins of $t/\tau(D^0)$** to have a better control on the resolution

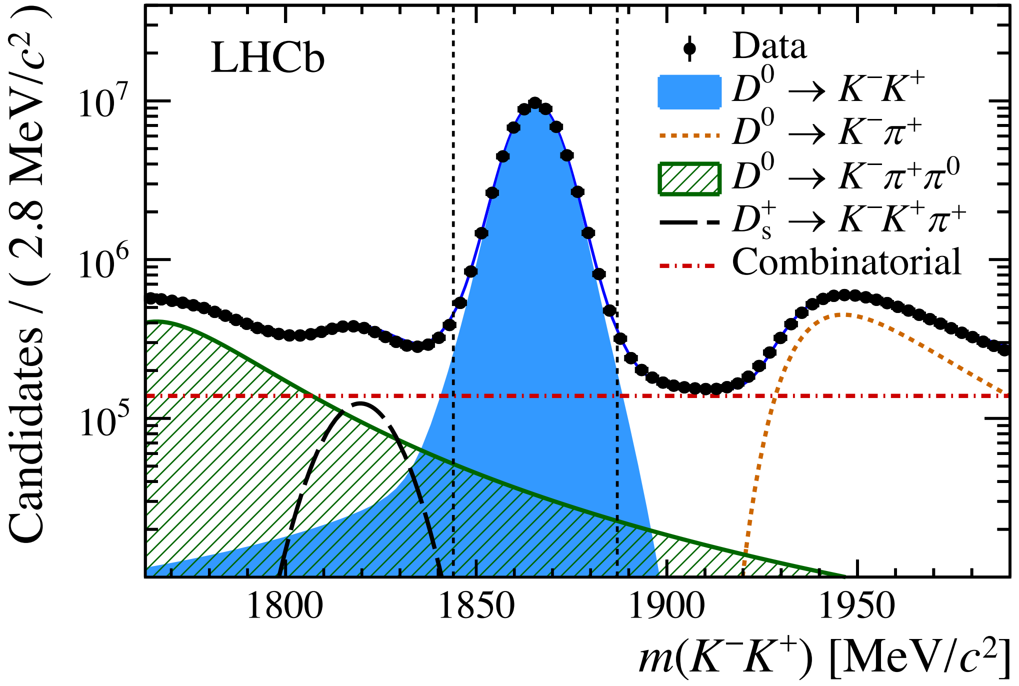
$$\text{TIP} = \frac{\hat{n}_z \wedge \vec{p}}{|\hat{n}_z \wedge \vec{p}|} \cdot (\vec{x}_{\text{DV}} - \vec{x}_{\text{PV}})$$



ΔA_{CP} – Peaking background (prompt)

The yields and raw asymmetries of $\boldsymbol{D^0 \to K^-\pi^+\pi^0}$ ($\boldsymbol{D^0 \to \pi^- l^+ \nu_l}$) are measured by fits to $m(K^-K^+)$ ($m(\pi^-\pi^+)$) and extrapolated to the signal region $[1844,1887]\ \mathrm{MeV}/c^2$





ΔA_{CP} – Difference in B^0 fraction (SL)

- Effective D^0 production asymmetry in SL B decays:

$$\boldsymbol{A_{\mathrm{P,eff}}(D^0)} = A_{\mathrm{P}}(B^+) + f(B^0)[A_{\mathrm{P}}(B^0) \cdot D - A_{\mathrm{P}}(B^+)]$$

- In Run 1 analysis: **difference in $\boldsymbol{f(B^0)}$** is $(0.34 \pm 0.18)\%$ between KK and $\pi\pi$ due to difference in B^0 and B^+ reconstruction **efficiencies**
- $\boldsymbol{A_P(B^0)}$ **and** $\boldsymbol{A_P(B^+)}$ measured by LHCb (PLB 774 (2017) 139)
- Conservative assumption → $f(B^0)$ difference is **1%**
  ➔ difference in $A_{\mathrm{P,eff}}(D^0)$ is $(-0.0001 \pm 0.0058)\%$
  ➔ take $\mathbf{1 \times 10^{-4}}$ as syst uncertainty

ΔA_{CP} – Difference in τ acceptance (SL)

- Effective D^0 production asymmetry in SL B decays:

$$\boldsymbol{A_{P,eff}(D^0)} = A_P(B^+) + f(B^0)[A_P(B^0) \cdot D - A_P(B^+)]$$

- That depends also on $D = 1 - 2\mathcal{P}_{osc}$, so also on **lifetime acceptance** (slightly different between KK and $\pi\pi$)

$$\mathcal{P}_{\text{osc}} = \frac{\Gamma_d}{2}\int_{t_0}^{\infty} e^{-\Gamma_d t}(1 - \cos(\Delta m_d t))\text{t}$$

- Syst uncertainty taken **unchanged** from Run1 analysis
  ➔ estimated to be maximum $\mathbf{2 \times 10^{-4}}$

Mistag rate (SL)

$$\delta_\omega = \Delta A_{CP} - \Delta A_{\text{raw}} = 2\omega_{KK} A_{CP}(K^-K^+) - 2\omega_{\pi\pi}[A_{CP}(K^-K^+) - \Delta A_{CP}] + 2A_{P,\text{eff}}(D^0)(\omega_{KK} - \omega_{\pi\pi}) + \Delta\omega_{KK} - \Delta\omega_{\pi\pi},$$

- Measure mistag on $\boldsymbol{D^0 \to K\pi}$ sample
- Take into account also **mixed** $D^0 \to K\pi$
- Use $A_{CP}(KK)$ and ΔA_{CP} from Run 1 SL
- Assume $\boldsymbol{A_{\mathrm{P,eff}}(D^0)} = 3\%$
- Systematic uncertainty is $\boldsymbol{4{\times}10^{-4}}$

Some theoretical references

Golden et. al., PLB 222 (1989) 501

Buccella et al., PRD 51 (1995) 3478

Bianco et al., Riv. Nuovo Cim . 26N7 (2003) 1

Grossman et al, PRD 75 (2007) 036008

Artuso et al., Ann . Rev. Nucl. Part. Sci. 58 (2008) 249

Khodjamirian et al., PLB 774 (2017) 235

Pirtskhalava et al. , PLB 712 (2012) 81

Cheng et al., PRD 85 (2012) 034036

Feldmann et al., JHEP 06 (2012) 007

Li et al., PRD 86 (2012) 036012

Franco et al., JHEP 05 (2012) 140

Brod et al., JHEP 10 (2012) 161

Atwood et al., PTEP 2013 (2013) 093B05

Hiller et al., PRD 87 (2013) 014024

Grossman et al., JHEP 04 (2013) 067

Müller et al., PRL 115 (2015) 251802

Buccella et al., (2019) arXiv:1902.05564

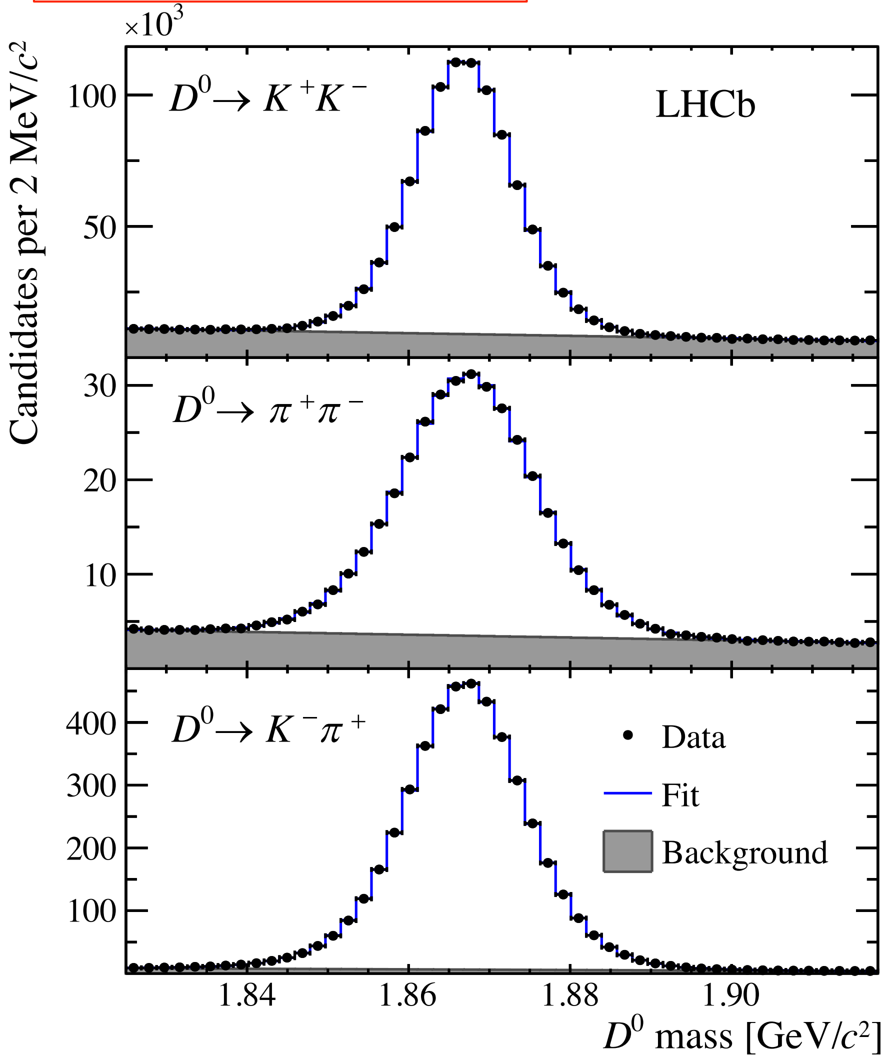
Measurement of y_{CP}

PRL 122 (2019) 011802

- Measure ratio between widths of D^0 decaying to *CP*-even (Γ_{CP+}) and to *CP*-mixed states (Γ):

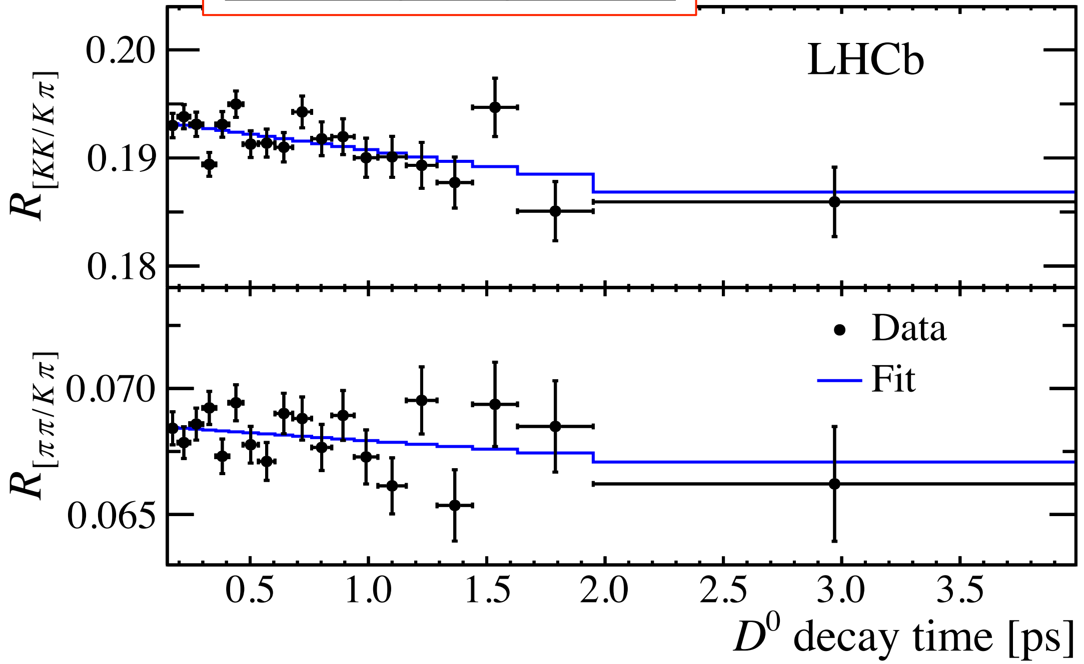
$$y_{CP} = \frac{\Gamma_{CP+}}{\Gamma} - 1$$

- If *CP* violated $\Rightarrow \boldsymbol{y_{CP} \neq y}$
- Measure $\boldsymbol{D^0 \to K^- K^+}$, $\boldsymbol{D^0 \to \pi^- \pi^+}$ and $\boldsymbol{D^0 \to K^- \pi^+}$ yields in bins of D^0 **decay time** t
- Fit signal **yields ratio** as function of t
- **Semileptonic** tag: D^0 from $\bar{B} \to D^0 \mu\nu X$
- Different **efficiencies corrected** by using simulation



Measurement of y_{CP}

PRL 122 (2019) 011802



- Procedure tested on **control samples** $D^+ \to K^+K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$
- Results **consistent** between K^+K^- and $\pi^+\pi^-$
- Results with Run 1 ($3\ \mathrm{fb}^{-1}$):

$$\boldsymbol{y_{CP} = (0.57 \pm 0.13\ (\mathrm{stat}) \pm 0.09\ (\mathrm{syst}))\%}$$

- Result compatible with and precise as the **WA** $(0.84 \pm 0.16)\%$
- Consistent with $y = (0.62 \pm 0.07)\% \Rightarrow$ **no *CP* violation**

Measurement of y_{CP}

PRL 122 (2019) 011802

- Most important systematic associated to the decay-time acceptance correction
- Other systematics:
  - Decay model and composition in simulation
  - Decay-time resolution
  - Fit model

Decay	Signal yield $[10^3]$
$D^0 \to K^+K^-$	878.2 ± 1.2
$D^0 \to \pi^+\pi^-$	311.6 ± 0.9
$D^0 \to K^-\pi^+$	4579.5 ± 3.2
$D^+ \to K^-\pi^+\pi^+$	2260.2 ± 1.9
$D^+ \to K^+K^-\pi^+$	98.0 ± 0.3

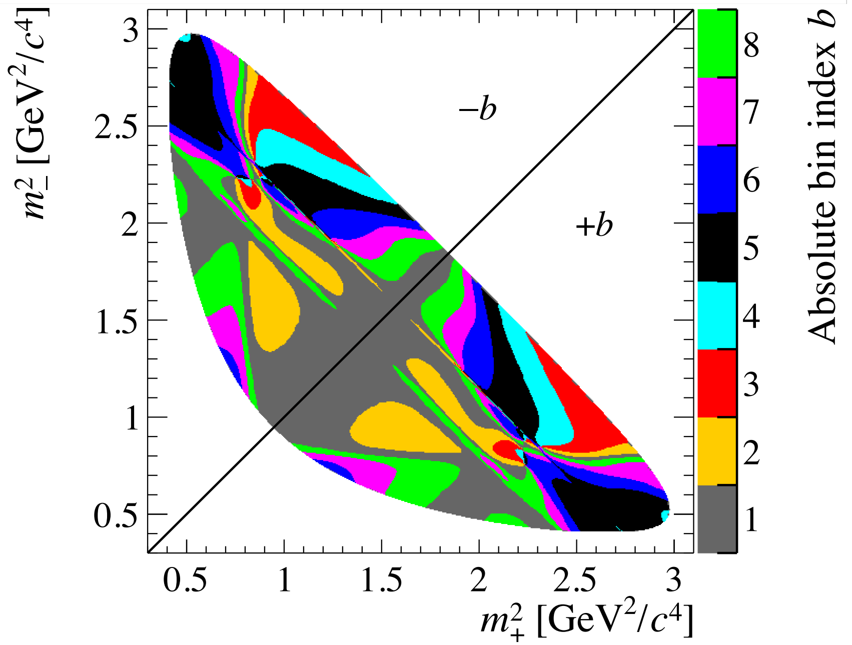
Decay	Δ_Γ $[\mathrm{ps}^{-1}]$	y_{CP} [%]
$D^0 \to K^+K^-$	$0.0153 \pm 0.0036 \pm 0.0027$	$0.63 \pm 0.15 \pm 0.11$
$D^0 \to \pi^+\pi^-$	$0.0093 \pm 0.0067 \pm 0.0038$	$0.38 \pm 0.28 \pm 0.15$

Measurement of x_{CP} and Δx

arXiv:1903.03074

- Analysis of $D^0 \to K_S^0\pi^+\pi^-$ → rich **resonance** substructure
- Use novel **bin-flip** method, which is model independent and avoids accurate modeling of the efficiency
- Binning in the **Dalitz** plane chosen to have almost constant strong-phase differences
- Measure yield ratio $\boldsymbol{R_{bj}^{\pm}}$ between $-b$ and b bins in decay time bin j
- $R_{bj}^{\pm}$ is function of $\boldsymbol{x_{CP}}$**,** $\boldsymbol{y_{CP}}$**,** $\boldsymbol{\Delta x}$ **and** $\boldsymbol{\Delta y}$
- $x_{CP} = x$, $y_{CP} = y$, $\Delta x = \Delta y = 0$ if CP conserved

$$m_{\pm}^2 \equiv \begin{cases} m^2(K_S^0\pi^{\pm}) & \text{for } D^0 \to K_S^0\pi^+\pi^- \\ m^2(K_S^0\pi^{\mp}) & \text{for } \bar{D}^0 \to K_S^0\pi^+\pi^- \end{cases}$$

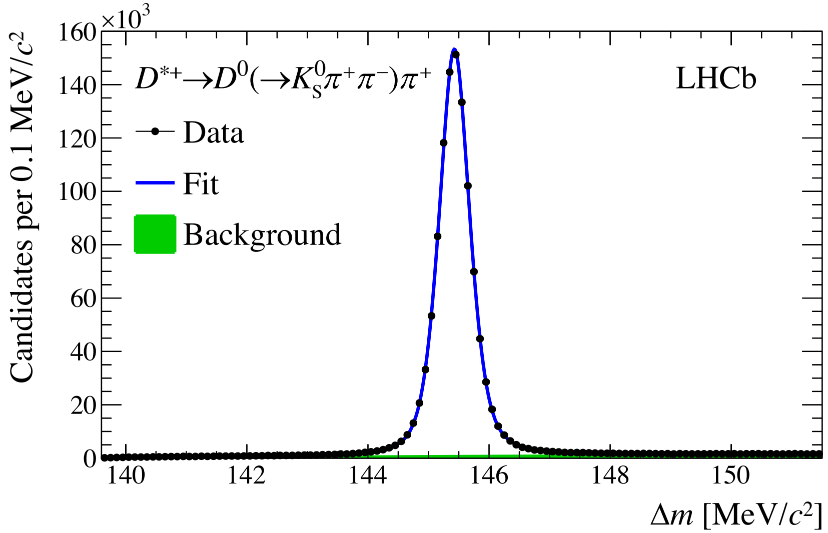


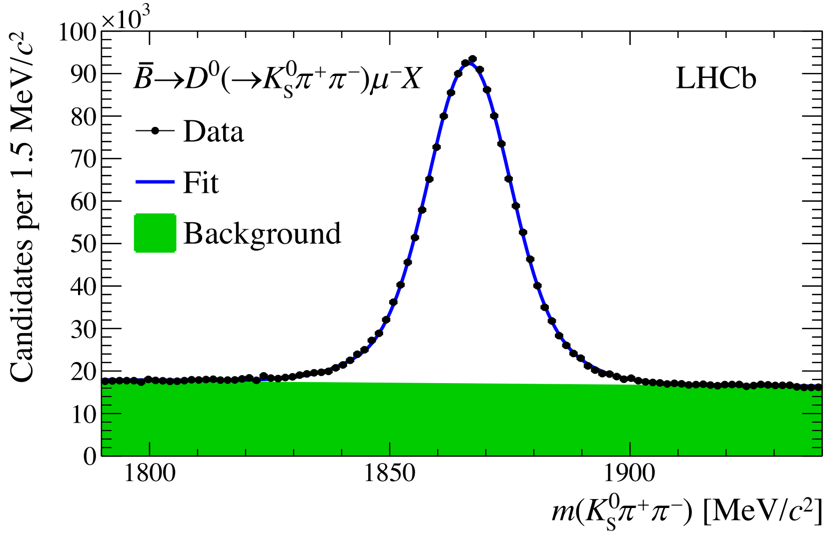
$$z_{CP} \pm \Delta z = -(q/p)^{\pm 1}(y \pm ix)$$
$$x_{CP} = -\mathrm{Im}(z_{CP}),\ y_{CP} = -\mathrm{Re}(z_{CP})$$
$$\Delta x = -\mathrm{Im}(\Delta z),\ \Delta y = -\mathrm{Re}(\Delta z)$$

Measurement of x_{CP} and Δx

arXiv:1903.03074

- Run 1 data ($\mathbf{3\ fb^{-1}}$)
- Both **prompt** and **semileptonic** tags are used
- Yield measured in **bins** of Dalitz, decay time, D^0 flavour, K_s^0 category
- A **fit** is performed to the decay-time dependence of $R_{bj}^{\pm}$ to obtain x_{CP}, y_{CP}, Δx and Δy





Measurement of x_{CP} and Δx

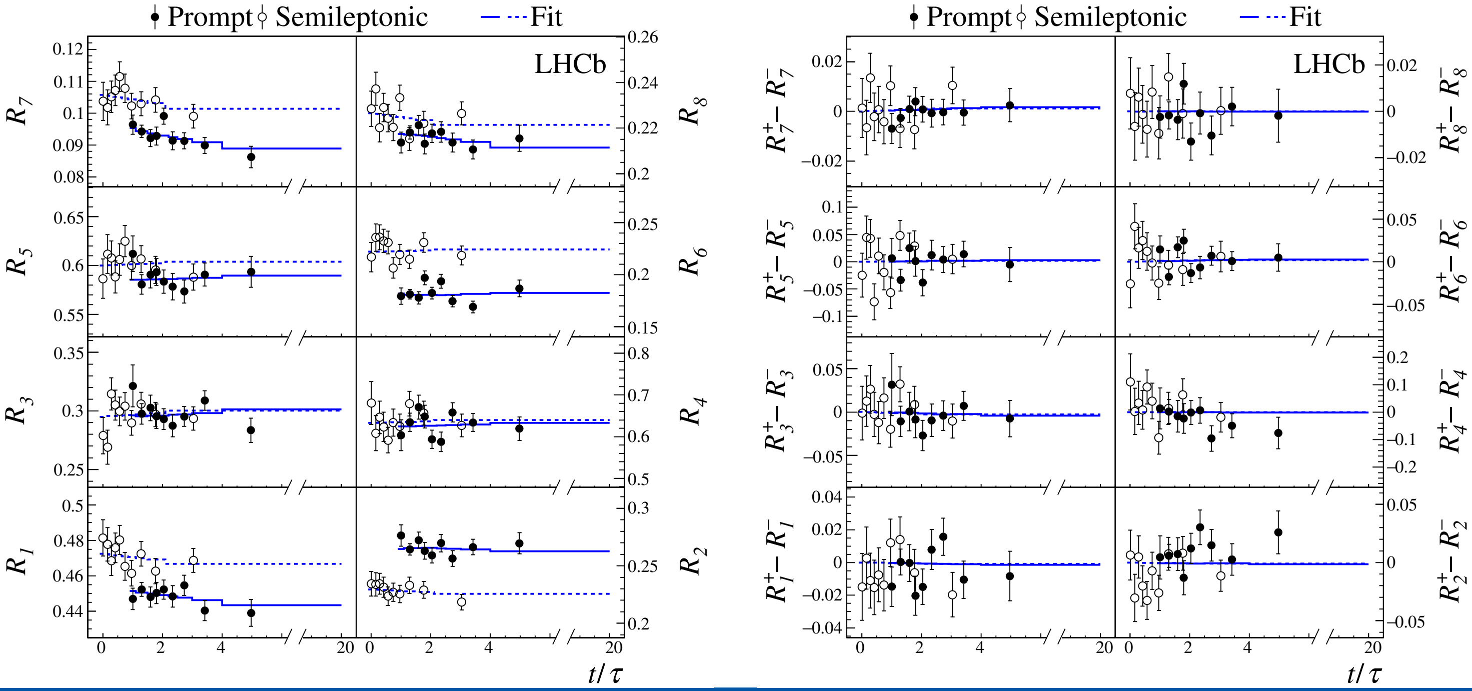
arXiv:1903.03074

- Results consistent with **no *CP* violation**
- **Most precise** determination of x from a single experiment

Parameter	Value	95.5% CL interval
x $[10^{-2}]$	$0.27^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
y $[10^{-2}]$	0.74 ± 0.37	$[\ \ 0.00, 1.50]$
$\lvert q/p \rvert$	$1.05^{+0.22}_{-0.17}$	$[\ \ 0.55, 2.15]$
ϕ	$-0.09^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

- Combination with current global knowledge gives $\boldsymbol{x > 0}$ at more than $\boldsymbol{3\sigma}$

Parameter	Value $[10^{-3}]$	Stat. correlations y_{CP}	Stat. correlations Δx	Stat. correlations Δy	Syst. correlations y_{CP}	Syst. correlations Δx	Syst. correlations Δy
x_{CP}	$2.7\ \pm 1.6\ \pm 0.4$	-0.17	0.04	-0.02	0.15	0.01	-0.02
y_{CP}	$7.4\ \pm 3.6\ \pm 1.1$		-0.03	0.01		-0.05	-0.03
Δx	$-0.53 \pm 0.70 \pm 0.22$			-0.13			0.14
Δy	$0.6\ \pm 1.6\ \pm 0.3$						



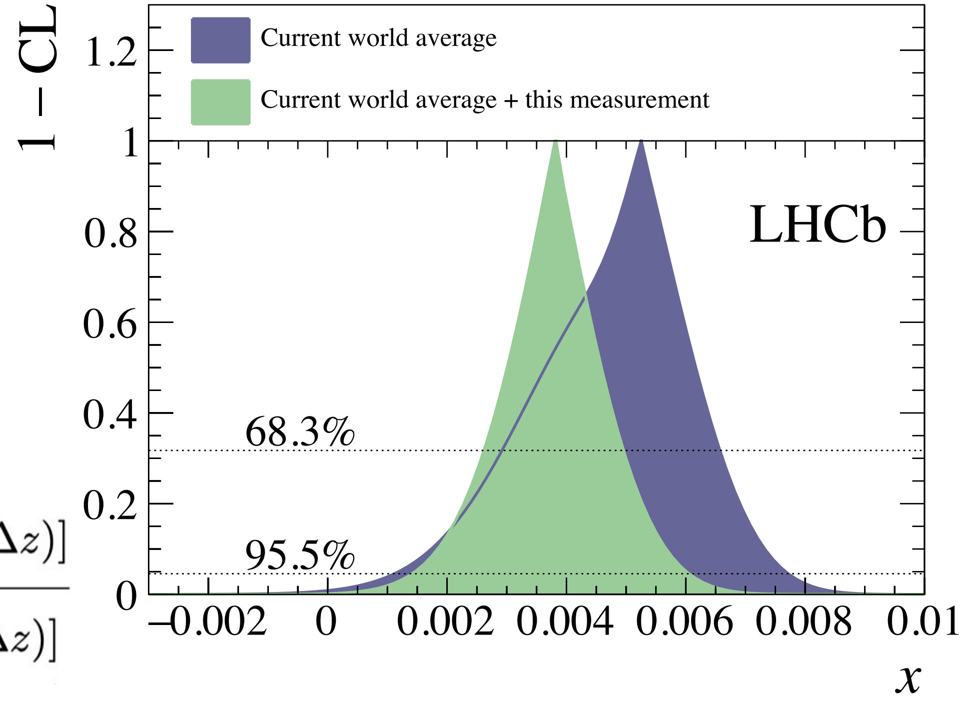
Measurement of x_{CP} and Δx

arXiv:1903.03074

- 1.3 M prompt
- 1.0 M SL
- Dominant systematic on x_{CP} is due to secondary D^0 for prompt and random μ for SL
- Decay-time, $m^2_{\pm}$ resolutions and efficiency in Dalitz plane dominate systematic of y_{CP}

Updated global combinations

Parameter	Value	Allowed interval 68.3% CL	95.5% CL	99.7% CL
x $[10^{-2}]$	0.38 ± 0.12	[0.26 , 0.50]	[0.14, 0.61]	[0.02, 0.71]
y $[10^{-2}]$	$0.655\,^{+0.062}_{-0.067}$	[0.588, 0.717]	[0.52, 0.78]	[0.44, 0.84]
$\lvert q/p \rvert$	$0.967\,^{+0.050}_{-0.045}$	[0.922, 1.017]	[0.88, 1.07]	[0.84, 1.13]
ϕ	$-0.070\,^{+0.079}_{-0.081}$	[−0.151, 0.009]	[−0.24, 0.09]	[−0.33, 0.19]



$$R^{\pm}_{bj} \approx \frac{r_b + \frac{1}{4} r_b \langle t^2\rangle_j \, \mathrm{Re}\left(z_{CP}^2 - \Delta z^2\right) + \frac{1}{4}\langle t^2\rangle_j \, \left|z_{CP} \pm \Delta z\right|^2 + \sqrt{r_b}\langle t\rangle_j \, \mathrm{Re}[X_b^*(z_{CP} \pm \Delta z)]}{1 + \frac{1}{4}\langle t^2\rangle_j \, \mathrm{Re}\left(z_{CP}^2 - \Delta z^2\right) + r_b \frac{1}{4}\langle t^2\rangle_j \, \left|z_{CP} \pm \Delta z\right|^2 + \sqrt{r_b}\langle t\rangle_j \, \mathrm{Re}[X_b(z_{CP} \pm \Delta z)]}$$

A_{CP} in $D_s^+ \to K_s^0\pi^+$, $D^+ \to K_s^0 K^+$, $D^+ \to \phi\pi^+$

- **Singly-Cabibbo-suppressed** decays
- $A_{CP} \sim 10^{-4} - 10^{-3}$
- Sensitive to **QCD** penguin and from chromomagnetic dipole operators (PRD 75 (2007) 036008)
- Already measured by LHCb with **Run 1** (JHEP 06 (2013) 112, JHEP 10 (2014) 025)

Channel	A_{CP} (%)	Dataset
$D_s^+ \to K_S^0\pi^+$	$+0.38 \pm 0.46$ (stat) ± 0.17 (syst)	2011-2012 (3.2/fb)
$D^+ \to K_S^0 K^+$	$+0.03 \pm 0.17$ (stat) ± 0.14 (syst)	
$D^+ \to \phi\pi^+$	-0.04 ± 0.14 (stat) ± 0.14 (syst)	2011 (1.1/fb)

A_{CP} in $D_s^+ \to K_S^0\pi^+, D^+ \to K_S^0 K^+, D^+ \to \phi\pi^+$

arXiv:1903.01150

- To cancel **production** and **detection** asymmetries, **control samples** are used: $D_s^+ \to K_S^0 K^+$, $D^+ \to K_S^0 \pi^+$, $D_s^+ \to \phi\pi^+$
- *CP* asymmetries are obtained from the raw asymmetries differences:

$$A_{CP}(D_s^+ \to K_S^0\pi^+) = [A(D_s^+ \to K_S^0\pi^+) - A_D(K^0)] - A(D_s^+ \to \phi\pi^+)$$

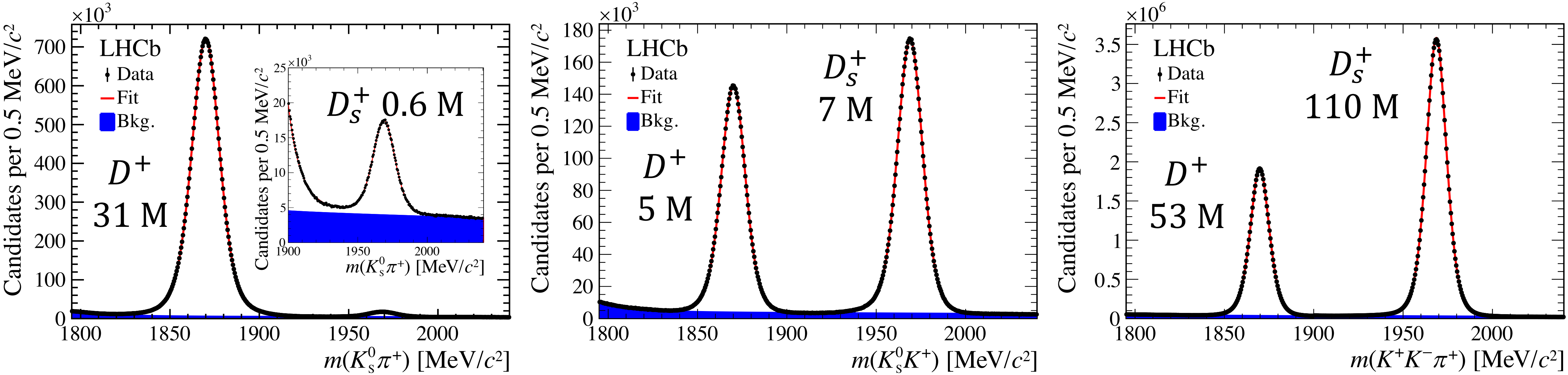
$$A_{CP}(D^+ \to K_S^0K^+) = [A(D^+ \to K_S^0K^+) - A_D(\bar{K}^0)] - [A(D^+ \to K_S^0\pi^+) - A_D(\bar{K}^0)] - [A(D_s^+ \to K_S^0K^+) - A_D(\bar{K}^0)] + A(D_s^+ \to \phi\pi^+)$$

$$A_{CP}(D^+ \to \phi\pi^+) = A(D^+ \to \phi\pi^+) - [A(D^+ \to K_S^0\pi^+) - A_D(\bar{K}^0)]$$

- Kinematics of $D_{(s)}^+$, π^+ and K^+ are weighted
- $\boldsymbol{A_{\mathrm{D}}(K^0)}$ is estimated by using simulation (JHEP 1407 (2014) 041)

A_{CP} in $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0K^+$, $D^+ \to \phi\pi^+$

arXiv:1903.01150



$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (\;\;1.3\;\; \pm 1.9\;\;(\text{stat}) \pm 0.5\;\;(\text{syst})) \times 10^{-3}$$

$$\mathcal{A}_{CP}(D^+ \to K_S^0K^+) = (-0.09 \pm 0.65\,(\text{stat}) \pm 0.48\,(\text{syst})) \times 10^{-3}$$

$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\;\;0.05 \pm 0.42\,(\text{stat}) \pm 0.29\,(\text{syst})) \times 10^{-3}$$

Run 2 - $3.8\ \text{fb}^{-1}$

No *CP* violation

A_{CP} in $D_s^+ \to K_s^0\pi^+$, $D^+ \to K_s^0 K^+$, $D^+ \to \phi\pi^+$

arXiv:1903.01150

Combination with Run 1

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (\ \ 1.6 \ \pm 1.7 \ \ (\text{stat}) \pm 0.5 \ \ (\text{syst})) \times 10^{-3}$$

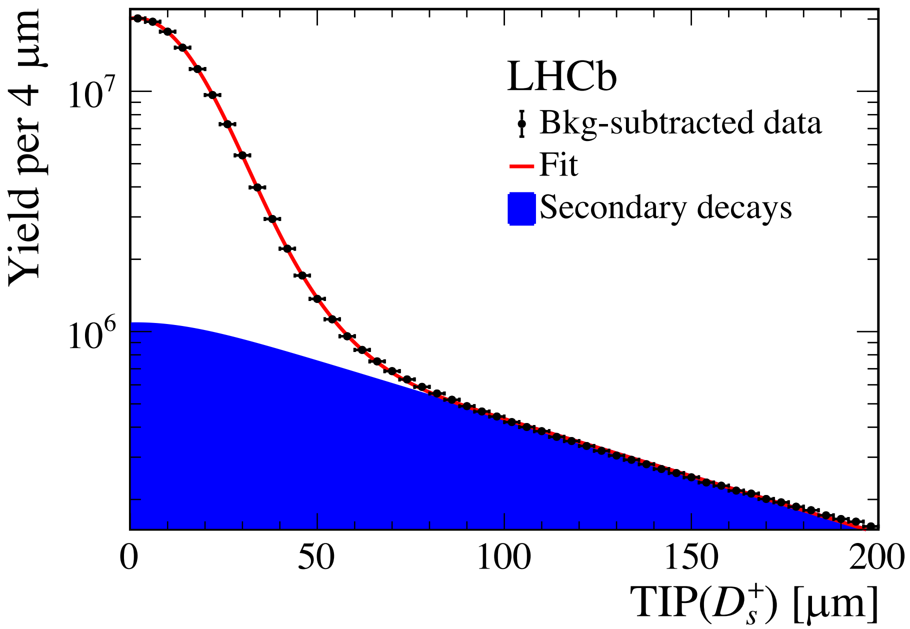
$$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) = (-0.04 \pm 0.61\,(\text{stat}) \pm 0.45\,(\text{syst})) \times 10^{-3}$$

$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.03 \pm 0.40\,(\text{stat}) \pm 0.29\,(\text{syst})) \times 10^{-3}$$

A_{CP} in $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0 K^+$, $D^+ \to \phi\pi^+$

arXiv:1903.01150

Systematic uncertainties
fit model and secondary decays are dominant



Source	$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+)$	$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+)$	$\mathcal{A}_{CP}(D^+ \to \phi\pi^+)$
Fit model	0.39	0.44	0.24
Secondary decays	0.30	0.12	0.03
Kinematic differences	0.09	0.09	0.04
Neutral kaon asymmetry	0.05	0.05	0.04
Charged kaon asymmetry	0.08	0.09	0.15
Total	0.51	0.48	0.29

CP in other charm decays at LHCb

Decay	Data sample	Tag
$D^0 \to K^+K^-\pi^+\pi^-$	Run 1 2011	SL PR
$D^0 \to \pi^+\pi^-\pi^+\pi^-$	Run 1	PR
$D^0 \to h^+h^-\mu^+\mu^-$	Run 1 + 2015 + 2016	PR
$D^0 \to \pi^+\pi^-\pi^0$	Run 1	PR
$D^+ \to \pi^+\pi^-\pi^+$	2011	-
$D^+ \to K^+K^-\pi^+$	2010	-
$D^+_{(s)} \to \eta'\pi^+$	Run 1	-
$\eta' \to \pi^+\pi^-$	Run 1	-
$\Lambda_c \to ph^+h^-$	Run 1	-